CHEMICAL ENGINEERING TRANSACTIONS
VOL. 40, 2014
Guest Editor: Renato Del Rosso

ISBN 978-88-95608-31-0; **ISSN** 2283-9216

A publication of AIDIC
The Italian Association of Chemical Engineering
www.aidic.it/cet

DOI: 10.3303/CET1440033

Odour Emission Factors: Fundamental Tools for Air Quality Management

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This paper discusses the importance odour emission factors (OEFs) and gives an indication of how to develop them, and organizing them in form of database, with the aim of allowing their continuous update.

1. Introduction

As a general rule, emission factors and emission inventories are fundamental tools for air quality management. Emission estimates are important for developing emission control strategies, determining applicability of permitting and control programs, evaluating the feasibility and the effects of appropriate mitigation strategies, and a number of other related applications by different users, including national and local agencies, consultants, and industry. Data from source-specific emission tests or continuous emission monitors are usually preferred for estimating a source's emissions. However, test data from individual sources are not always available and, even then, they may not reflect the variability of actual emissions over time. Thus, emission factors are frequently the best or only method available for estimating emissions, in spite of their limits (US EPA, 1995).
Currently, the most complete compilation of pollutant emission factors is the AP 42 by the United States Environmental Agency, which up to now is constituted by 15 chapters including different sections, each covering a different activity sector, ranging from food and agricultural industries to petroleum industry or waste disposal, and many others. Up to now, this compilation refers to "traditional" pollutants, but not to odours. However, as a matter of fact, odours are now recognized as atmospheric pollutants and are subject to control and regulation in many countries (Nicell, 2009; Sironi et al., 2013). For this reason it appears very important to extend the existing databases of emissions factors to odours, thus defining "odour emission factors" (OEFs).

2. State-of-the-art: EPA Emission Factors from AP-42

2.1 Definition of Emission Factors

An emission factor is a representative value that attempts to relate the quantity of a pollutant released to the atmosphere with an activity associated with the release of that pollutant. These factors are usually expressed as the weight of pollutant divided by a unit weight, volume, distance, or duration of the activity emitting the pollutant (e.g., kilograms of particulate emitted per ton of coal burned). Such factors facilitate estimation of emissions from various sources of air pollution. In most cases, these factors are simply averages of all available data of acceptable quality, and are generally assumed to be representative of long-term averages for all facilities in the source category (i.e., a population average).
The general equation for emission estimation is:

$$E = A \, x \, EF \, x \, (1 - \frac{ER}{100})$$

Where E is the emission, A the activity rate, EF the emission factor, and ER the overall emission reduction efficiency (%). ER is further defined as the product of the control device destruction or removal efficiency and the capture efficiency of the control system. When estimating emissions for a long time period (e.g.,

Please cite this article as: Capelli L., Sironi S., Del Rosso R., 2014, Odour emission factors: fundamental tools for air quality management, Chemical Engineering Transactions, 40, 193-198 DOI: 10.3303/CET1440033

one year) both the device and the capture efficiency terms should account for upset periods as well as routine operations.

Emission factor ratings in AP-42 provide indications of the robustness, or appropriateness, of emission factors for estimating average emissions for a source activity. Usually, data are insufficient to indicate the influence of various process parameters such as temperature and reactant concentrations. However, emission factor formulae that account for the influence of such variables tend to yield more realistic estimates than would factors that do not consider those parameters.

2.2 Uses of Emission Factors

Emission factors may be appropriate to use in a number of situations such as making source-specific emission estimates for areawide inventories. These inventories have many purposes including ambient dispersion modelling and analysis, control strategy development, and in screening sources for compliance investigations. Emission factor use may also be appropriate in some permitting applications, such as in applicability determinations and in establishing operating permit fees.

Use of emission factors as source-specific permit limits is not recommended by EPA. Because emission factors essentially represent an average of a range of emission rates, approximately half of the subject sources will have emissions rates greater than the emission factor and the other half will have emission rates less than the factor. As a consequence, using an AP-42 emission factor would result in half of the sources being in noncompliance.

3. Odour Emission Factors (OEF)

OEFs are developed in analogy with the emission factors defined by the US EPA (1995) for other pollutants/chemical compounds (Sironi et al., 2005). In this case, the equation for odour emission estimation becomes:

$$OER = A\ x\ OEF\ x\ (1 - \frac{ORE}{100})$$

Where OER is the odour emission rate (in ou_E/s), A the activity index, and ORE the overall odour reduction efficiency (%); and the ORE can be calculated as follows:

$$ORE = \frac{c_{od,IN} - c_{od,OUT}}{c_{od,IN}} \cdot 100$$

Where $c_{od,IN}$ and $c_{od,OUT}$ are respectively the odour concentrations at the inlet and at the outlet of the abatement system (Sironi et al., 2007).

OEFs can be derived from experimental or literature data by first identifying a suitable activity index, which should ideally be related to the quantity of odour emitted, and then by dividing the emitted odour emission rate by this activity index, which may be for example the gross weight production, the site surface or a time unit.

In general, OEFs can be used for odour impact assessment as input data for the application of specific odour dispersion models. OEFs also can have a predictive value: they allow to estimate the odour emission rate (OER) associated with an industrial plant even before its construction. Moreover, OEFs may be applied in order to predict how the odour impact of an industrial plant will be influenced by plant modifications. As a matter of fact, nowadays, most odour regulations all over the world are defined based on the application of dispersion modelling. The wide diffusion of this approach is due on one hand to the fact that odour dispersion modelling is relatively cheap and results are easily understandable. On the other hand, another compelling reason for the use of odour dispersion modelling is the ability to apply it in advance of construction of a new plant, thus being "predictive", and not solely "descriptive", as field measurement are. Of course, in order to apply odour dispersion modelling to predict odour impact of a plant, it is mandatory to be able to predict the entity of its odour emissions (in terms of ou_E/s), which are required as model inputs.

OEFs would therefore represent a simple and effective means to predict the odour emissions from a given plant typology, using one (or more) parameter (activity index) related to the odour emission itself. Of course, OEF, despite their simplicity, allow a rather "rough" estimation of odour emission rates, but knowing the order of magnitude of the odour impact expected is in most cases sufficient in order to evaluate the appropriateness of the location of a new plant or the design of possible odour control systems.

In general, the development of emission factors should be based on specific olfactometric data, which can be derived from: a) reference files, b) technical journals (e.g., sectorial journals, conference papers), c) emission databases, d) references from environmental agencies/ other institutions, e) references from industry or sectorial associations. Scientific literature in the field of olfactometry is rather recent, however, a considerable amount of information about the odour concentrations related to different kinds of emissions are currently available. Unfortunately, these data are generally presented with different logics and thus hardly comparable. Moreover, they are often not related to important parameters, such as air flow rates or other significant details allowing to characterize plant typology and dimensions. Nonetheless, there are some recent studies and documents published by local or event international agencies giving specific indications about odour emission factors. Some examples are given in the following sections.

4. Examples of OEFs

4.1 OEFs from composting operations

There are several papers investigating the emissions of volatile organic compounds from composting operations (Smet et al., 1999; Komilis et al., 2004), but papers reporting odour concentrations or odour emission rates from composting facilities are not frequent.

A paper by Sironi et al. (2006) reports OEF resulting from of odour concentration measurements that were carried out from 2000 to 2005 on 40 plants for the mechanical-biological treatment (MBT) of municipal solid waste (MSW) located all over the Italian territory. About 50 air samples were collected on each plant, giving a total of about 2,000 samples, and the odour sources considered for the study are represented by the different process steps: a) MSW receiving, b) green waste receiving, c) aerobic biological treatment, d) curing, e) finished product heaps storage, f) overscreen heaps storage. The OEFs were evaluated separately for each process step, and they were related to the plant capacity. As a consequence OEFs result from the ratio between the average OER value associated to each step, obtained as geometric mean of the average OER values for each plant, and the plant capacity, and are therefore expressed in $ou_E\ t^{-1}$ (Table 1). The last row of Table 1 refers to the plants without open air emission sources in which the only emission is represented by a mixture of the waste gases collected from all process steps.

Table 1: Average OEFs, median and per cent deviation for each step of the MSW composting process

	Geometric mean of OEF ($ou_E\ t^{-1}$)	**Median of OEF ($ou_E\ t^{-1}$)**	**% Deviation**
Waste receiving (rec)	1.26E+06	1.11E+06	5.0%
Green waste receiving	3.02E+05	3.30E+05	9.9%
Aerobic biological treatment (bio)	1.40E+07	1.27E+07	6.1%
Green waste aer. biol. treatment	1.25E+06	5.25E+05	12.2%
Curing (cur)	3.99E+06	2.99E+06	7.4%
Overscreen storage (os)	2.42E+05	3.20E+05	12.0%
Final product storage (fp)	7.54E+05	9.25E+05	8.3%
All process steps	1.19E+07	1.25E+07	6.5%

As already mentioned, OEFs van be used in order to estimate the overall emissions (In terms of OER) of a plant. According to Sironi et al. (2006) the overall OER (in $ou_E\ s^{-1}$) relevant to a composting facility can be obtained as the product of the plant capacity and the sum of the OEFs relevant to each process step:

$$OER_{TOT} = C \cdot (OEF_{rec} + OEF_{bio} + OEF_{cur} + OEF_{os} + OEF_{fp})$$

If any process step is carried out in sheds with an air collection system that conveys the waste gases to an abatement system, the effective OER of the plant can be calculated by multiplying the single OEFs by a term that takes account of the efficiency of the adopted abatement system.

OEFs can also be used in order to compare the entity of the odour emissions associated with each process step: the aerobic biological treatment represents the major odour source of a composting facility (OEF ~ 10^8 $ou_E\ t^{-1}$). However, there are also other process steps having high OEF values, such as the curing, waste receiving and final product storage (OEF ~ 10^7 $ou_E\ t^{-1}$), thus suggesting that also these phases should be confined in dedicated sheds and not conducted open air, in order to limit odour nuisance problems.

4.2 OEFs from wastewater treatment

Odour emissions have always been one of the main concerns associated to wastewater treatment. For this reason, there are several scientific papers about odour characterization (Kim et al., 2002), quantification (Gostelow et al., 2001) and abatement (Estrada et al., 2010) in wastewater treatment plants. However, specific olfactometric data are rarely reported in literature (Gostelow and Parsons, 2000).

Also in this case, there has been an attempt by Capelli et al. (2009a) to develop OEFs for the different treatment phases of the wastewater depuration cycle, including: -a) wastewater arrival (WW-arr), b) pre-treatments (pre-tr), c) primary sedimentation (I-sed), d) de-nitrification (denitr), e) nitrification (nitr), f) oxidation (oxi), g) secondary sedimentation (II-sed), h) chemical-physical treatments (ch-ph), i) sludge thickening (sl-thi), j) sludge storage (sl-st).

In this case, the OEF calculation was based on the olfactometric data (in total, 211 samples) coming from 17 different plants located all over Italy, treating mostly municipal wastewaters, with different treatment capacities ranging from a minimum of 1000 m^3 d^{-1} and a maximum of 800000 m^3 d^{-1}. The yearly treatment capacity was assumed as activity index for WWTPs, based on experimental evidences that prove the existence of a correlation between conferred wastewater quantity and emitted odour quantity, giving that the OEFs are expressed as odour units emitted per cubic metre of wastewater treated (ou_E m^{-3}).

The results of the study show that the major odour source of a wastewater treatment plant is represented by the primary sedimentation (with an OEF equal to $1.9 \cdot 10^5$ ou_E m^{-3}). In general the highest OEFs are observed in correspondence of the first steps of the wastewater depuration cycle (OEF between $1.1 \cdot 10^4$ ou_E m^{-3} and $1.9 \cdot 10^5$ ou_E m^{-3}) and tend to decrease along the depuration process (OEF between $7.4 \cdot 10^3$ ou_E m^{-3} and $4.3 \cdot 10^4$ ou_E m^{-3}) (Table 2).

Table 2: Average OEFs, median and per cent deviation for each treatment phase of the wastewater depuration cycle

	Geometric mean of OEF (ou_E m^{-3})	**Median of OEF (ou_E m^{-3})**	**% Deviation**
Wastewater arrival	1.09E+04	3.09E+03	40%
Pre-treatments	1.05E+05	3.42E+05	26%
Primary sedimentation	1.90E+05	1.18E+05	17%
De-nitrification	9.15E+03	6.27E+03	17%
Nitrification	7.35E+03	6.91E+03	22%
Oxidation	1.21E+04	1.72E+04	19%
Secondary sedimentation	1.31E+04	1.34E+04	13%
Chemical-physical treatments	8.25E+03	1.09E+04	15%
Sludge thickening	4.25E+04	4.99E+04	19%
Sludge storage	8.26E+03	1.02E+04	17%

It is important to observe that, given the source typology being considered, i.e., passive area sources without a flow rate, samples had to be collected by means of specific hoods (wind tunnels) that have the function of simulating wind action on the sampled surface, thus allowing to associate a flow rate to the measured odour concentration and estimate an odour emission rate (Capelli et al., 2009b). As a consequence, OER values and therefore also OEFs obtained with this method are a function of the air velocity on the sampled surface (or the wind speed). The data reported in Table 2 are referred to a reference velocity of 0.3 m s^{-1}, but they can be re-calculated for any other velocity using the following equation, which is derived from the Prandtl boundary layer theory (Sohn et al., 2005):

$$OER_{v2} = OER_{v1} \left(\frac{v_2}{v_1}\right)^{\frac{1}{2}}$$

The use of OEFs for the estimation of the overall OER relevant to a WWTP provides to calculate the OER as the product of the plant treatment capacity and the sum of the OEFs relevant to each of the odour sources that are present on the considered plant.

Both on the case of composting facilities and of WWTOs OEFs were referred solely to the plant capacity. An improved estimation could be achieved by further refining the OEFs, by evaluating their dependence from other parameters, such as for example, temperature, humidity, organic content of the treated waste or BOD.

4.3 OEFs from livestock operations

In many countries, intensive livestock represent an important source of pollution, especially in terms of ammonia and odours. This is the reason why, especially in Nord-European countries (i.e., Denmark, Germany, England and The Netherlands), livestock are already subject to specific studies and regulations (Groot Koerkamp et al., 1998). As an example, the Austrian and German approach provide to calculate minimum separation distances between livestock buildings and residential areas to avoid odour nuisance, based on a dispersion model developed by Schauberger et al. (2012a; 2012b).

For the sector of the Intensive Rearing of Poultry and Pigs, for the first time, a reference document of the European Commission on Best Available Techniques (European IPPC Bureau, 2013), besides reporting emission factors for ammonia and dust refereed to different animal categories, also indicates emission factors specifically for odour, expressed as odour unit emitted per animal (ou_E s^{-1} $animal^{-1}$) (Table 3).

Table 3: OEFs for the intensive rearing of poultry and pigs, as reported in the new draft of the Best Available Techniques (BAT) Reference Document of the European Commission

Parameter	Animmal category	BAT AEL ou_E s^{-1} per animal
Odour	All type of poultry	0.2-0.5
Odour	All types of pigs	6-30

In analogy with the other plant typologies described in the previous paragraphs, OEFs are considered as constant values, which means that the odor emission rate is treated as constant. This assumption appears particularly untrue for the case of animal houses, where odour emissions are known to be strongly influenced by animal activity, as well as by other parameters, such as indoor temperature and barn ventilation rate. For this reason, for a more accurate and reliable estimation of odour emissions, OEFs should be calculated as function of these parameters.

One interesting attempt to "refine" OEFs for swine housing has been made by Schauberger et al. (2013), who developed an empirical swine odor emissions model to reduce the bias caused by indoor temperature, air velocity, and animal activity (Figure 1).

Figure 1 reports the live mass specific odor emission factor, expressed in odour units per second and per live mass of animal unit (1 AU = 500 kg) for different seasons calculated by Schauberger's model (solid lines) compared by another time course proposed by Nicholas et al. (2002) (dashed lines). The thin line indicates the mean odor emission factor assumed to be equal to 48 ou_E s^{-1} AU^{-1} for both datasets.

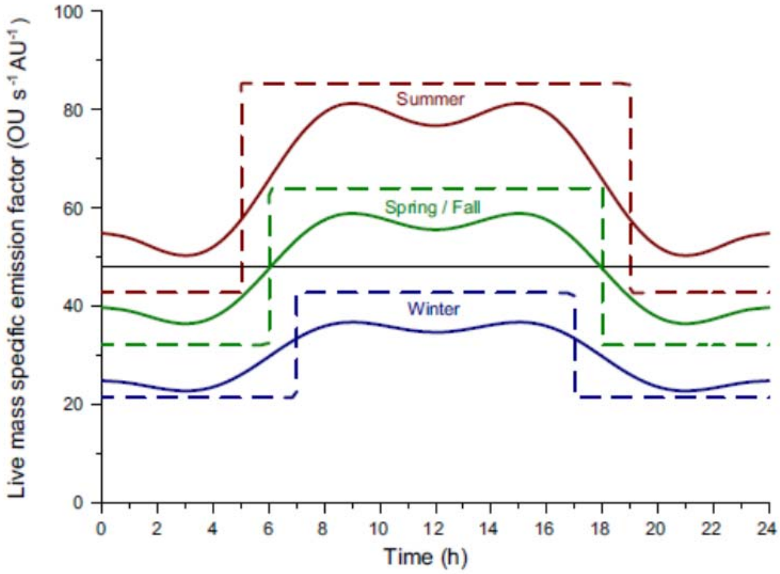

Figure 1: Diurnal course of the live mass specific odor emission factor

5. Conclusions

OEFs represent a simple and effective means to predict the odour emissions from, using one (or more) parameter (activity index) related to the odour emission itself.

The examples reported in this paper clearly show that OEFs should be evaluated separately for each plant typology, in order to address the specificities of each plant typology (e.g., source types, parameters affecting odour emissions, etc.)

Of course, OEFs, despite their simplicity, allow a rather "rough" estimation of odour emission rates, but knowing the order of magnitude of the odour impact expected is in most cases sufficient in order to evaluate the appropriateness of the location of a new plant or the design of possible odour control systems. OEFs may be further "refined" and improved by evaluating their dependence from more parameters than just one activity index, such as atmospheric conditions or seasonality.

Ideally, OEFs should be organized in form of a database, in analogy with the existing compilations of emission factors for other pollutants, with the aim of making it possible to update them continuously, for instance by inserting or varying the data used for the OEF calculation.

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