CHEMICAL ENGINEERING TRANSACTIONS

VOL. 43, 2015

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

Chief Editors: Sauro Pierucci, Jiří J. Klemeš

ISBN 978-88-95608-34-1; **ISSN** 2283-9216

DOI: 10.3303/CET1543359

The Evaluation of the Odour Emission Rate for Passive Area Sources: a New Approach

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Usually the Odour Emission Rate (OER) for passive area sources is evaluated by means of a ventilated hood: a forced air flow is insufflated from an air cylinder in the hood in order to mimic the action of the wind and obtain a value for the emissivity of the source. The obtained OER is therefore estimated at a fixed speed – the predetermined rate of the airflow – so it is necessary to recalculate it at the proper wind speed for every instant of the time domain of the simulation. This can be done exploiting the dependence of the Odour Emission Rate on the flow rate and thus the speed; generally the speed used for this operation is the one obtained from the meteorological station. In the present work a new approach is discussed, arguing the legitimacy of the procedure just described, since for several reasons the wind speed detected at the station level may be significantly different from the one at the level of the source. In the paper it will be discussed how to obtain a better procedure capable of computing more reliable OER terms so to provide better final results. The discussion will revolve around the different classes of formulas to evaluate the wind speed at the desired height – namely logarithmic or power law – and will conclude with an overview of the most promising correlations.

1. Background

It is known that odours resulting from human activities cause nuisance to the population and have been included in the atmospheric contaminants. It is necessary to underline that odours cause the most of people's complaints to local authorities. This is a consequence of the fact that several conventional pollutants (e.g. NO, CO, CH_4,…) are generally not perceived, even if they might be harmful for humans, while some odours are perceived far below normal exposure limit concentrations (few ppbs), due to the presence of compounds having low odour detection threshold concentration (Nicell, 2003).
Odours are nowadays subject to control and regulation in many countries. The necessity to regulate odour impacts implies intrinsically the development/application/validation of specific methods for odour measurement and quantification (Sironi, 2014). Dynamic olfactometry (EN 13725, 2003) is now a widespread technique for the quantification of odour emissions in terms of odour concentration. Source characterization is not sufficient to account for the effective impact of odours on the public. In order to properly evaluate citizens' exposure to odours, it would be helpful to quantify odours directly at the receptors, in the field. Sadly, odour measurement in the field is a complicated task (Gostelow, 2001). These issues explain the increasing interest in odour impact assessment approaches relying on dispersion modelling. The odour dispersion models allow to simulate how most likely the emitted odour will disperse in the atmosphere, in a certain area for a specific emitting source or set of emitting sources. Such models allow to evaluate ground-level odour concentration values in the simulation space-time domain (Capelli, 2011), thus having the advantage of being not only descriptive (as field measurements), but predictive as well. Most odour regulations worldwide define guidelines based on the application of atmospheric dispersion modelling (EPA, 2007). Odour regulations may establish acceptability standards in terms of the frequency of the exceeding of a given odour concentration threshold (UK-EA, 2002). E.g. the approach adopted by the UK-EA 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 the 2% of the hours in a year (for the case of a one-year domain). The limits set by the guidelines are expressed in terms of hourly averaged odour concentration values at the 98th percentile. In

Please cite this article as: Lucernoni F., 2015, The evaluation of the odour emission rate for passive area sources: a new approach, Chemical Engineering Transactions, 43, 2149-2154 DOI: 10.3303/CET1543359

other examples, odour regulations specify the minimum distance from the closest inhabited area where possible odoriferous facilities can be located. Historically, minimum distances were tabulated, by taking into account the land use or the residential density of the area in which the facility was located. More recently, minimum distances are not being tabulated but calculated by direct application of proper dispersion models or by using simplified mathematical expressions containing specific coefficients derived from dispersion modelling. Different models can be used to simulate the dispersion of pollutants into the atmosphere. Independently from the model chosen, validation is fundamental in order to evaluate model reliability and its possible application. Concerning odour dispersion models, it is necessary to provide three sets of data.

1.1 Meteorological data

The acquisition and pre-processing of meteo data is of crucial importance for atmospheric dispersion modelling (Vankatram, 2004). Meteo data required for dispersion modelling include: wind speed, wind direction, information about the atmospheric stability conditions, which can be derived from other meteorological parameters, such as humidity, temperature and wind speed profiles, as well as cloud covering or solar radiation. The detail and quality of the input data requirements depend on the level of sophistication of the model chosen. First dispersion models - i.e. simple Gaussian plume models - rely on the usage of the Pasquill-Gifford-Turner stability classes for the characterization of the vertical and lateral dispersion. Conversely, the new generation of short-range dispersion models, including more complex Gaussian plume models, use Monin-Obukhov similarity to describe the mean and turbulent structure in the surface boundary layer. The ground-level concentration is generally expressed in terms of specific variables, such as the surface friction velocity and the Monin-Obukhov length, which hold information on the turbulence and the mean wind velocity, the quantities that govern dispersion. More sophisticated, non-steady-state models - i.e. Lagrangian puff models, Lagrangian particle models, Eulerian models, hybrid models - all share the common characteristic that they can process as input a 3D dataset of meteo info. In principle, meteo data could be obtained from one single meteorological station.

1.2 Topographical data

The spatial domain of the simulation should be chosen as to include all the emission sources to be studied, as well as all the receptors that are believed to be impacted by the emitted odours and their geographical coordinates shall be indicated. Also, if the orography of the terrain included in the spatial simulation domain falls in the complex terrain category, its effects shall be taken into account in the simulations, by adopting suitable algorithms and properly setting the elevations of each receptor point of the simulation grid (Canepa, 2004).

1.3 Emission data

It is not sufficient to consider the pollutant (odour) concentration, but it is also mandatory to account for the air flow associated with the monitored odorigenous source. In the peculiar case of odour, the parameter to be considered for dispersion modelling is the Odour Emission Rate (OER), which is expressed in European odour units per second (ou_E s^{-1}) and is obtained as the product of the odour concentration and the air flow associated with the source. The volumetric air flow shall be evaluated in normal conditions for olfactometry, defined as it follows: 20°C and 101325 Pa on wet basis (EN, 13725, 2003). The method for the evaluation of the OER coming from an odour source depends on the source typology. For this reason, different sampling strategies should be adopted in function of the source to be monitored. In the case of point sources, where odour is emitted from a single point, sampling consists in the withdrawal of a fraction of the conveyed air flow. In this case the OER can be obtained as it follows:

$$OER = Q_{air} * c_{od} \; [\frac{ou_E}{s}] \quad (1)$$

With

$$Q_{air} = v_{air} * A_{stack} \; [\frac{m^3}{s}] \quad (2)$$

Where

OER = Odour Emission Rate (ou_E s^{-1})
Q_{air} = effluent volumetric air flow (m^3 s^{-1})
c_{od} = measured odour concentration (ou_E m^{-3})
A_{stack} = stack's transversal section (m^2)
v_{air} = effluent flow speed (m s^{-1})

For the case of area sources, where emissions typically come from extended solid or liquid surfaces, it is first necessary to make a distinction between active and passive area sources. Active area sources, have a significant outflow, above 50 m^3 h^{-1} m^{-2} as defined by the German Guideline VDI 3880 (VDI 3880, 2011), whereas passive area sources have no out-coming air flow and the mass flow from the surface solid/liquid phase to the air gas phase is due to phenomena such as equilibrium or convection. In some cases it may be useful to introduce a third category, semi-passive area sources, tailored for emissive sources that have a minimal out-coming air flow. In the case of active area sources, sampling is carried out by means of a “static” hood that isolates a part of the emitting surface, channelling the outward air flow into the hood outlet duct, realizing the same configuration as in the case of point sources, so that the OER can be evaluated applying the same expression used for point sources. In the case of passive area sources, the estimation of the OER is a complicated operation, as it is difficult to measure a representative odour concentration and, most of all, it is hard to determine a well-defined air flow rate for the scenario. Hood methods - whereby emission rates are derived from the data regarding the concentration of the compounds of interest measured in the samples collected at the outlet of the sampling device in combination with the dimensions of the device itself and the operating conditions - are by far the techniques that are most widely used for the evaluation of emission rates from passive area sources. Various sampling devices have been designed and tested for sample collection from a range of different area sources. All these devices are based on the same principle: isolating a portion of the emitting surface by means of a hood, to insufflate a neutral air stream and finally to measure the odour concentration at the hood outlet. The estimation of the OER requires in this situation the calculation of another significant parameter, the Specific Odour Emission Rate (SOER), expressed in European odour units emitted per surface and time unit (ou_E m^{-2} s^{-1}), as it is expressed formulaically in the following equation:

$$SOER = Q_{air} * \frac{c_{od}}{A_{base}} \left[\frac{ou_E}{s*m^2}\right] \quad (3)$$

Where

$SOER$	=	Specific Odour Emission Rate (ou_E m^{-2} s^{-1})
Q_{air}	=	air flow rate inside the hood (m^3 s^{-1})
c_{od}	=	measured odour concentration (ou_E m^{-3})
A_{base}	=	base area of the hood (m^2).

The OER can be then calculated by multiplying the SOER by the emitting surface of the considered source:

$$OER = SOER * A_{em} \left[\frac{ou_E}{s}\right] \quad (4)$$

Where

OER	=	Odour Emission Rate (ou_E s^{-1})
$SOER$	=	Specific odour Emission Rate (ou_E m^{-2} s^{-1})
A_{em}	=	emitting surface area of the considered source (m^2).

For passive area sources, an important aspect to be considered is that the OER can be expressed as a function of the air flow above the emitting surface. In the case of liquid surfaces, by applying the Prandtl boundary layer theory, it is possible to demonstrate that both the SOER and the OER are proportional to the square root of the air velocity above the monitored surface (Sohn, 2005). Due to this fact, all dispersion models should account for this significant dependence and thus it is required to re-calculate the OER for each hour of the simulation time domain according to the actual wind speed at that moment. The formula allowing this computation is here reported:

$$OER_{v_2} = OER_{v_1} * \left(\frac{v_2}{v_1}\right)^{1/2} \quad (5)$$

Other odour sources that might be considered for dispersion modelling are the so-called diffuse volume sources, typically buildings from which odours come out. It is not always possible to correctly characterize the emissions from such sources, since it is difficult to measure a representative odour concentration and, often, it is not possible to define exactly the out-coming air flow. Besides the OERs relevant to any kind of source (point, area, or diffuse), other data are required as inputs. Firstly, the geographical location of the sources should be identified as precisely as possible in the simulation spatial domain. Furthermore, the exact geometry of the source should be identified - e.g., height, diameter, orientation – and implemented. Also, the physical data of the emission like air flow/wind speed and temperature need to be specified as well. In the case of odour dispersion modelling, the major contribution to the global uncertainty in the results is given by the emission data, due to the olfactometric analysis intrinsic uncertainty. Measurement uncertainty may vary significantly among different laboratories and it is generally much lower for laboratories working in accordance to the European Standard for dynamic olfactometry (EN, 13725, 2003). It is possible to find studies proving that the uncertainty of dynamic olfactometry can add up to ±6 dB_{od}, which means an error band between one fourth and the fourfold of an actual measurement value (Capelli, 2013).

After an introduction, it is possible to move on to the core of the matter; the present work aims to make an assessment about the best procedure to evaluate the so-called Odour Emission Rate (OER) for the case of passive area sources that is the area sources lacking a distinct outflow.

2. Methods

In order to go on with the discussion it might be useful to remind how to re-calculate the OER according to wind speed for the case of passive area sources; the dependency on the wind speed has useful implications, in facts normally OER is evaluated at a standard wind speed and then it is re-calculated with the actual value of the wind speed for each hour of the time domain of the simulation; this can be done in accordance with Eq.(5). Usually the OER is re-calculated with the wind speed taken from the meteo data. A lot of reasoning was done around this crucial step in the impact assessment and a detailed inspection brought about a possible significant error in this procedure: in facts, the wind speed used for the estimation of the correct OER is generally the one recorded at the meteorological station. This peculiarity is what triggered the author's concern, since this wind speed is the one observed at the station height while the OER should depend on the wind conditions at the emitting source height. Several meters of difference in elevation above ground can have a great impact on the final outcome: wind speed changes, OER changes, and impact changes. A good amount of research was carried out in order to find possible ways to account for this fact, and excogitate how to evaluate the correct height, the correct wind speed and the proper OER. In the end three possible laws were highlighted that can be used for the evaluation of the wind speed at a certain desired height. It is worth specifying that this applies only to OER evaluation for passive and semi-passive area sources, where the air flow is artificially induced; in point sources and active area sources the flow is measured thus the OER does not have to be recalculated.

2.1 The Power Law Equation

The first correlation evaluated is the so-called "Power Law" (Cook, 1997): the desired speed is evaluated starting from a known value of the speed (i.e. the one recorded at the station) and the "Hellman's parameter" (α) that is usually recovered from specific tables. The "Power Law Equation" is here reported (De Marrais, 1959):

$$v_{wind}^{h_1} = v_{wind}^{h_2} * \left(\frac{h_1}{h_2}\right)^{\alpha} \quad (6)$$

Where

v_w^{h1} $= wind\ speed\ at\ the\ correct\ height\ (m\ s^{-1})$
v_w^{h2} $= wind\ speed\ at\ the\ meterological\ station\ height\ (m\ s^{-1})$
h_1 $= correct\ height\ (m)$
h_2 $= the\ metereological\ station\ height\ (m)$
α $= Hellman's\ parameter\ (-)$

A more detailed explanation is due; the "correct height" is here intended as the height significant for the emission source thus for the impacts on the receptors: while for single sources there are no troubles, when multiple sources are present, a general emission height needs to be established and two options are available; either compute the height by means of an odour concentration weighted average of all sources height or compute it by means of a simple arithmetic mean neglecting the height of the least significant emitting sources (least "impacting", smallest influence on the overall impact). Furthermore, as far as the so-called Hellman's parameter is concerned, usually its proper values are obtained from specifically prepared tables, where the exponent is provided as a function of the atmospheric stability class - unstable A/B/C, neutral D, stable E/F/G - and the landscape typology (rural, urban, coastal, water…). An example of these tables is here reported:

Table 1: Table for estimation of the Hellman's parameter

Rural Land		Urban Land	
Stability	α	Stability	α
A	0.1	A	0.15
B	0.15	B	0.15
C	0.2	C	0.2
D	0.25	D	0.25
E	0.25	E	0.4
F, G	0.3	F, G	0.6

2.2 The Modified Logarithmic Law Equation

The second correlation proposed is the "Modified Logarithmic Law" that directly evaluates the wind speed at the desired height relying on micro-meteorological parameters such as friction velocity and Monin-Obukhov length and an "atmospheric stability parameter" (Ψ) as shown by the formula here reported (Bonan, 2005):

$$v_w^{h1} = \frac{u_*}{K_v} * \left[LN\left(\frac{h_1 - \delta}{z_0}\right) + \Psi * \left(\frac{h_1}{L_{MO}}\right)\right] \quad (7)$$

Where

v_w^{h1} $= wind\ speed\ at\ the\ correct\ height\ (m\ s^{-1})$
h_1 $= correct\ height\ (m)$
u_* $= friction\ velocity\ (m\ s^{-1})$
K_v $= Von\ Karman's\ constant,\ usually\ about\ 0.40 - 0.41\ (-)$
δ $= zero\ plane\ displacement,\ usually = 0.67 * h_c\ (m)$
h_c $= average\ canopy\ height\ (m)$

$z_0 \quad = surface\ roughness\ length\ (m)$
$L_{MO} \quad = Monin - Obukhov\ length\ (m)$
$\Psi \quad = stability\ factor;$ it $depends\ on\ the\ atmospheric\ stability\ class\ (-)$

Also in this case further explanations are due. As stated, the Ψ depends on the stability class, namely:

- For neutral conditions, class (D), Eq.(8) holds true

$$\Psi = 0 \tag{8}$$

- For stable conditions, classes (E, F, G), Eq.(9) holds true

$$\Psi = -5 * \left(\frac{h_1}{L_{MO}}\right) \tag{9}$$

- For unstable conditions, classes (A, B, C), Eq.(10) holds true

$$\Psi = 2 * LN\left(\frac{1+x}{2}\right) + LN\left(\frac{1+x^2}{2}\right) - 2 * arctg(x) + \frac{\pi}{2} \tag{10}$$

The (x) is a correction factor evaluated as it follows:

$$x = \left[1 - 16 * \left(\frac{h_1}{L_{MO}}\right)\right]^{1/4} \tag{11}$$

2.3 The Logarithmic with Parabolic Defect Law Equation

The last correlation considered is the "Deaves-Harris Law" (Cook, 1997) - also known as the logarithmic with parabolic defect model equation – that calculates the wind speed through a polynomial expression. The expression of this law is here shown in the following equation (Khalifa, 2014):

$$v_w^{h1} = \frac{u_*}{K_v} * \left[LN\left(\frac{h_1}{z_0}\right) + 5.75 * \left(\frac{h_1}{H}\right) - 1.88 * \left(\frac{h_1}{H}\right)^2 - 1.33 * \left(\frac{h_1}{H}\right)^3 + 0.25 * \left(\frac{h_1}{H}\right)^4\right] \tag{12}$$

Where

$v_w^{h1} \quad = wind\ speed\ at\ the\ correct\ height\ (m\ s^{-1})$
$h_1 \quad = correct\ height\ (m)$
$u_* \quad = friction\ velocity\ (m\ s^{-1})$
$K_v \quad = Von\ Karman's\ constant,\ usually\ about\ 0.40 - 0.41\ (-)$
$z_0 \quad = surface\ roughness\ lenght\ (m)$
$H \quad = equilibrium\ boundary\ layer\ height;\ usually = \frac{u_*}{6f_c}\ (m)$
$f_c \quad = Coriolis'\ parameter = 2 * \Omega * \sin(\varphi)\ \ (s^{-1})$
$\Omega \quad = Earth\ rotation\ rate;\ generally\ taken\ as = 7.2921 * 10^{-5}\ (rad/s)$
$\varphi \quad = latitude\ (rad)$

This concludes the discussion on wind speed recalculation formulas.

3. Results and discussion

In the following section the advantages and disadvantages of the different options will be presented.
It seems reasonable to proceed displaying the pros and cons of each possible choice concerning wind speed for OER estimation purposes. First option is to use the data coming from the meteorological station; this is what is commonly done, many pre-processing softwares follow this procedure which does not require extra calculations and is widely accepted. Second option is to use the Power Law expression; this is the simplest and most general wind speed recalculation formula, it is reliable at any height even if it is suggested especially for heights from 100 meters up. Third option is to use the Modified Logarithmic Law expression; this correlation is generally more precise than the Power Law for heights between 0 and 100 meters. Unfortunately there are some critical points in the formula, especially concerning the zero plane displacement length and the stability factor. Due to these problems sometimes the usage of this equation produces bad results. Fourth option is to use the Logarithmic with Parabolic Defect Law expression; this is the Deaves-Harris formula, it has a rather convoluted form but it is a very reliable equation that can be used in a wide range of applications.
The two best choices appear to be options n.2 and n.4, due to the intrinsic error in option n.1 and the tricky application of option n.3. This fact can be better appreciated looking at the elucidative Table 2 here reported:

Table 2: Table of results obtained comparing the discussed procedures

	v_wind [m/s]	OER [ou/s]
Default	0.7	59039.65
Power Law	0.43	47051.87
Modified Log Law	0.41	46039.88
Deaves-Harris Law	0.2	33622.77

Table 2 refers to the same scenario, same emitting source and same time-space domain; the OER is evaluated according to Eq.5 making use of the wind velocity calculated with the different methods. The scenario refers to a single passive area source emitting odoriferous gases in a plane area. Once more it is clear how the default value of velocity has as a direct consequence the over-estimation of the source's emission rate. The modified logarithmic law in the considered scenario could be used smoothly, but its application in different situations might be problematic. Therefore the choice should fall onto either the Power Law method or the Deaves-Harris Law method.

4. Conclusions

The present work aimed to shed some light on the complicated procedure of OER assessment for passive area sources, inspecting the dependence with wind velocity and discussing what value should be considered. The possible pathways to obtaining the velocity to be used in the OER estimation were presented and afterwards they were weighed. Finally, a hint is given on which ones look more promising at the moment.

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