Use of CFD For Sampling Hood Design: An Example For Methane Flux Assessment on Landfill Surfaces

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ABSTRACT

This study provides a method and a set of guidelines for the assessment of landfill gas surface emissions. The work focuses on the principles for the design of a specific static hood and on the definition of an optimal sampling procedure. This is carried out by means of computational fluid dynamics (CFD) simulations to investigate the fluid dynamics conditions of the hood. The study proves how CFD may be as useful tool for the design and evaluation of sampling systems, thus corroborating the principle that understanding the fluid dynamic conditions is fundamental in order to understand the sampling results and correctly interpret the measured concentration values by relating them to a suitable volatilization model, and therefore to estimate emission rates. The procedure here discussed, which is specific for the case of the investigated landfill, can be generalized to be applied also to different scenarios, where hood sampling is involved.

Keywords: landfill gas; emissions assessment; computational fluid dynamics; passive area sources; static hood; flux chamber.

1. INTRODUCTION

Environmental sampling for the assessment of emissions from area sources is a quite complicated task (Capelli et al., 2013). The most widely-used techniques for the evaluation of emission rates from area sources the so called “hood methods”, involve an enclosure of some sort. Emission rates are then derived from the data regarding the concentration of the compounds of interest, measured in the samples collected at the outlet of the sampling device combined with the dimensions of the device and the operating conditions (Hudson and Ayoko, 2008; Jiang and Kaye, 1996).

Sampling on landfill surfaces for the assessment of landfill gas (LFG) emissions is even more problematic, due to the specific characteristics of this kind of source; in facts, although surely it is not an active area source, it cannot be considered as a passive area source neither, as the landfill surface is typically crossed by a low flux, and there is currently no widely accepted method for sampling on landfills (Bogner et al., 1995; Rachor et al., 2013; Reinhart et al., 1992; Sarkar et al., 2002). Landfills have always been considered important sources of atmospheric pollution, mainly due to the emissions of landfill gas (LFG) from the landfill surface, which entails the emissions of greenhouse gases, VOCs and unpleasant odours (Davoli et al., 2003; Palmiotto et al., 2014; Park and Shin, 2001; Sironi et al., 2005). For this reason, the development of specific methods for the assessment of the emissions would be of great interest both for environmental authorities and for landfill managers and operators (Capelli et al., 2015).

In the scientific community, it is possible to find a certain agreement concerning the kind of device that should be used for methane concentration measures on landfill surfaces: the instrument should be a static accumulation box of some sort. The hood should allow the methane to diffuse in the internal volume undisturbed (i.e. no external flow) making it possible to measure the concentration over time and then obtain the LFG emission flux. There are several possibilities for the static hood design, as there are different proposals found both in regulations and in scientific papers (UK EA, 2010; Rachor et al., 2013; Lucernoni et al., 2015).

47 In truth, there is an alternative for methane concentration measures on landfill surfaces, which is the
48 procedure exploiting a specifically designed Flux Chamber device, as suggested by the US EPA (Klenbusch,
49 1986). In the present study, the Static Hood was preferred for logistical reasons, linked to the high neutral
50 air demand when operating with a Flux Chamber. Moreover, in a previous research, it was proved that the
51 results obtained with the two methodologies – on the same source – are very much alike (Capelli et al.,
52 2014); thus, it is possible to use either one of the two methods.

53 The present study aims to provide a method and a set of useful guidelines for the design of a static
54 chamber to be used in LFG surface emissions measurements. Moreover, the study aspires to provide hints
55 on what should be the most appropriate sampling methodology to adopt in the field. This will be carried
56 out by means of computational fluid dynamics (CFD) simulations of the phenomenon. Anyway, the
57 procedure here discussed, specific for the case of the investigated landfill, can be applied also for different
58 scenarios, where for a different site the goal is to design a hood analogue to the device here presented.

59 As a result, this project will try to corroborate the idea that CFD is a useful tool and can be effectively
60 applied to the design and evaluation of sampling hoods, as discussed in recent studies in this field (Prata Jr.
61 et al., 2016). This idea is based on the fact that the study of the fluid dynamic conditions inside any type of
62 sampling hood is fundamental to understand the sampling results and correctly interpret the measured
63 concentration values by relating them to a suitable volatilization model, in order to be able to estimate
64 emissions.

65 **2. SAMPLING ON LANDFILL SURFACES: STATE OF THE ART**

66 As aforementioned, even though the hood typology for this kind of inquiries is established – i.e. static
67 hoods – there are different proposed designs presented in the scientific literature. In particular, three
68 designs are considered.

69 The first design is the passive flux box proposed by the British regulation (UK EA, 2010). It consists of an
70 enclosure of known volume, with two ports on the top: one inlet port is used for pressure equilibration
71 while the other one, i.e. the outlet port, is used for withdrawing gas samples. Its main design features are: a

simple enclosure with an open base that covers an area of approximately 0.33 - 1 m^2; two controlled openings on the top; a sampling line and a suitable gas detection system (e.g., a portable gas detector, such as a flame ionization detector, FID) for methane concentration measurement inside the box . The device is typically made of plastic, about 150 mm high. Some sort of paddle may be fitted within the box to promote gas mixing (UK EA, 2010). The need for this additional tool depends on the box dimensions and the emission flux rate. The flux boxes should have a base area less than 1 m^2 and a pyramidal shape. A typical flux box scheme as described in the UK guideline is shown in Fig. 1.

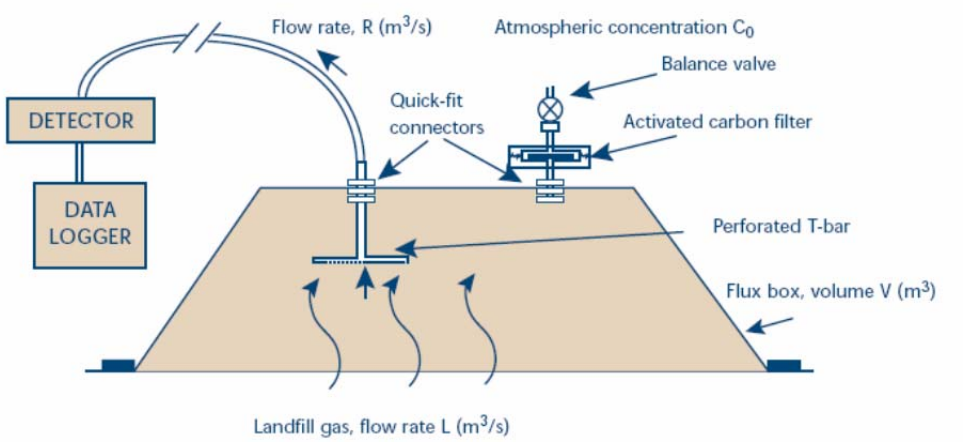


Figure 1. Typical UK EA passive flux box scheme (UK EA, 2010).

The device depicted in Fig. 1 shows a reasonable compromise between footprint area, volume to footprint ratio, ease of construction and practicability on site. The sample must be withdrawn at a point where the gas is representative of the mixture in the flux box. The sampled volume must not be so great as to cause significant dilution of the remaining gas. From the measured concentration, it is possible to obtain the emission according to Eq.1:

$$Q = \frac{V_{sb}}{S_{sb}} \cdot \left(\frac{dc}{dt}\right) \quad (1)$$

Where Q is the methane emission flux in [mol m^{-2} s^{-1}], V_{sb} is the volume of the sampling device in [m^3], S_{sb} is the base area of the sampling device in [m^2], c is the methane concentration variation in [mol m^{-3}] and t is the considered time period in [s].

90 The second design is the one proposed in 2013 by a German research group (Rachor et al., 2013). In this
91 case, the device consists of a cylindrical aluminium chamber with a height of 0.5 m and a base area of 0.12
92 m^2. The base of the chamber is sharpened in order to enable a better insertion into the soil to a depth of
93 few centimetres, which is necessary in order to avoid undesired exchanges of air/gas between the interior
94 and exterior of the chamber. Gas tightness is further guaranteed by the presence of a water-saturated
95 foam on the hood outside. Even though the hood practically works as a static chamber, its functioning has
96 been improved by preventing overpressures inside the chamber due to the emission of landfill gas from the
97 soil: the chamber has in facts an open tube (inner diameter 4 mm) connecting the inner volume with the
98 atmosphere. The tube has been designed long enough (3m) as to compensate for possible pressure
99 differences without allowing significant gas exchange by diffusion. Moreover, the chamber is equipped with
100 three sampling ports connected to a switching valve. As described in the paper by Rachor et al. (2013), their
101 mobile analyser (FID) for the methane concentration measurement inside the chamber, was connected to
102 the valve, logging CH_4 concentrations every minute. The adopted sampling procedure provides that 15
103 seconds before logging takes place, the open tube was closed and the valve to the chamber opened. Given
104 the suction flow rate of the FID (approximately 1 l/min) and the quick instrumental response time (5 s), this
105 procedure prevents the withdrawal of too much gas, which, according to the authors, produced stable and
106 representative readings. As stated in the above mentioned paper, chamber operation according to this
107 procedure usually lasted at least 6 minutes. Gas emissions from the landfill can be calculated from the CH_4
108 concentration measured inside the chamber according to Eq. 2:

109
$$E = \frac{p \times m \times V_{Ch} \times 1440}{10^6 \times R \times T} \quad (2)$$

110 Where E is the methane rate of emission in [mol_{CH_4}/day], p is the ambient pressure in [hPa], m is the slope
111 of the linear regression (C_{gas}/t) in [µmol/mol/min], V_{Ch} is the actual volume of the chamber in [l], R is the gas
112 constant in [J/mol/K] and T is the temperature in the chamber in [K].

113 The third design is the one adopted in the present work, which will described in the following section.

3. MATERIALS AND METHODS

3.1 The sampling hood developed at LabOlf

The design adopted in this study, consists of a steel static hood with a square base area. The hood realized at POLIMI LabOlf is based on the first design proposed, relying on theoretical considerations, inspired as well by the scientific literature (Rachor et al., 2013; UK EA, 2010). The sampling chamber has a 50 cm x 50 cm base: this allows to cover a representative portion of the landfill surface, while granting that the internal volume is adequate for the Flame Ionization Detector (FID) operation. In facts, the FID adopted for CH_4 concentration measurement is a Crowcon GasTec FID that sucks about 1,06 l/min for a measure time of 2 min, amounting to a total of 2 l circa. This implies that the hood needs to have a volume at least 10 times greater than that value. The device needs also to be easily transportable, i.e. reasonably small dimension, since the sampling points are scattered over a quite large surface. Therefore, a height of 10 cm was chosen (i.e. a chamber volume of 25 l); this value is significantly lower than the 50 cm proposed by Rachor et al. (2013) but it was chosen considering that the phenomenon is mainly diffusive and thus slow. The POLIMI hood is made of steel, a resistant material that allows to insert the hood in the soil without damaging it and minimizing the undesired LFG leaks; the hood is equipped with lateral flanges assuring a determined penetration into the turf in order to grant a fixed effective hood volume of 25 l in all measurements. The chamber is also equipped with 2 pipes: the former 3 m long, located on a lateral wall that assures isobaric conditions during sampling; the latter 10 cm long, located on the top of the chamber that is the sampling port for the FID. The short tube determines also the exact sampling point, where the CH_4 is measured. Such point needs to grant a measure representative of the average concentration inside the hood, in order to have useful results. The position of the sampling point should vary according to the hood height and the emitted LFG flow, since as these two variables change, the average concentration and the concentration distribution in the chamber will change as well. It is easy to understand that this is a very delicate choice and that it is important to investigate how the sampling point position varies for different situations. An example of such chamber is depicted in Fig. 2.

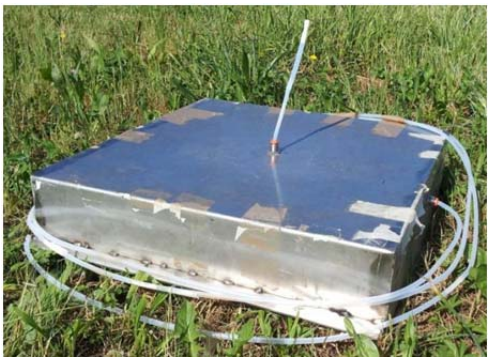


Figure 2. The POLIMI LabOlf static hood.

The sampling lasts about 10 min of hood deposition time plus 2 min of FID operation. Hypothesizing that the methane concentration measured at the sampling point is representative of the average concentration in the hood and that the concentration growth over time in the considered horizon time is linear, it is possible to compute the LFG emission according to Eq. 3. The two hypothesis made will be verified by means of CFD simulations.

$$\hat{Q}_{LFG} = \frac{c_{CH_4,mis} \cdot V}{c_{CH_4,LFG} \cdot \Delta t \cdot S_h} \quad (3)$$

Where $\hat{Q}_{LFG}$ is the LFG emission flux in [l m^{-2} s^{-1}], V is the volume of the sampling device in [l], S_h is the base area of the sampling device in [m^2], $c_{CH_4,mis}$ is the measured methane concentration in [ppm], $c_{CH_4,LFG}$ is the methane concentration in the LFG in [ppm] and t is the measure time in [s].

As mentioned above, in order to determine the specific LFG flow rate emitted from the landfill surface, the hood is positioned over the soil, for a period defined in 10 min (Lucernoni et al., 2015), then the CH4 concentration is measured with the FID. The time of 10 minutes was fixed based on two main considerations. The former, it is a sufficient time to obtain readable CH_4 concentration values inside the hood. In facts, in a work by Palmiotto et al. (2014), which describes a study carried out on a Municipal Solid Waste (MSW) landfill in Lombardy, the evaluated mean LFG emission rate turned out to be 0.2 l/m^2/h, giving a concentration of few hundreds ppm inside the hood after 10 minutes, which can be read with the FID. The latter, is that a period of 10 minutes is short enough to assume that the concentration grows linearly with time, even if it has an asymptotic “plateau” trend.

159 Actually, the nature of the phenomenon is almost purely diffusive and the sampling hood can be modeled
160 as a Plug Flow Reactor (PFR). After a certain time, the methane concentration inside the hood will reach a
161 stationary value (i.e. the methane concentration in LFG, 50%). In order to have a rough estimation of the
162 time required to reach the plateau, it is possible to compute the ratio between the hood volume and the
163 LFG flow rate, which for the case here considered – with a LFG emission in the range of the tenths of $l/m^2/h$
164 – turned out to be 24000 min circa. For this reason, it is reasonable that in the first 10 minutes the CH_4
165 concentration growth inside the hood can be approximated with a linear trend.

166 The study shows how CFD can be a useful tool for the design of a suitable sampling procedure for particular
167 and complex area sources requiring the use of specific sampling hoods (Prata Jr. et al., 2016).

168 **3.2 Computational Fluid Dynamics (CFD)**

169 Computational Fluid Dynamics (CFD) is the field of fluid mechanics that uses numerical analysis and
170 software to solve problems concerning fluid flows, heat transfer and chemical reactions. The chosen
171 software for the present work was ANSYS Fluent v14.5, one of the most used and most validated CFD
172 program available in the market (Fluent User's Guide, 2012). This software helped in defining the most
173 appropriate sampling procedure, allowing to verify whether or not the first design proposed for the hood
174 and the sampling methodology devised were acceptable, in terms of hood dimensions, sampling point and
175 measurement time.
176 In CFD analysis the control volume is divided into numerous cells, and the nonlinear partial differential
177 equations (PDEs), which govern the system, are discretized and solved numerically. So, in order to perform
178 the simulations, some steps have to be done:

179 1) Define and create the model geometry
180 2) Create the mesh
181 3) Set up the solver and choose the proper physical models

182 For steps 1 and 2, the grids were built with the aid of the software GAMBIT, which allows to define the
183 mesh with the desired characteristics. This is very important, in order to guarantee accuracy and

184 convergence of the FLUENT solution. The meshes were made of tetrahedral cells and presented a
185 "boundary layer" in order to increase accuracy in proximity of the inlet.
186 Then, the boundary conditions need to be defined. The base surface of the hood was set as *mass flow inlet*,
187 the outlet surface of the 3 m long tube (during the 10 min deposition time) as *pressure-outlet*, and the
188 outlet surface of the 10 cm long tube (during the 2 min FID operation) as *velocity-inlet*.

189 For step 3, in the present case the equations considered were those for the mass, momentum and energy
190 conservation, and for the species transport, which allows to account for the diffusion of the LFG – a binary
191 gas mixture of CH_4 and CO_2 – in air.

192 After setting up the whole case, it is possible to run the simulation. When the simulation has finished, a
193 built-in post-processor allows to visualize and investigate the results.

194 It is worth clarifying that the "deposition time" in the present work refers to the period when the chamber
195 is put on top of the sampling area and no induced flows are present. After this "deposition time" is the "FID
196 operation time", the period when the FID is turned on sucking a defined flow rate from the chamber.

197 **3.3 CFD Simulations**

198 In order to verify the hypotheses discussed in Par. 3.1, allowing to devise a proper hood design
199 methodology and an adequate sampling procedure, several simulations were set up and performed. In
200 different simulations, key parameters were changed such as hood height and LFG emitted flow, while the
201 base surface of the hood is kept constant. Tab.1 summarizes the different input data set for each
202 simulation.

203 *Table 1 Summary of the performed simulations.*

Simulation	Q_{LFG} [l/(m^2*h)]	Hood Height [cm]	Number of cells	Number of layers of the boundary layer
1	0.25	10	~ 2.7 million	7
2	0.05	10	~ 2.7 million	7
3	1.00	10	~ 2.7 million	7
4	0.25	20	~ 3 million	21
5*	0.25	10	~ 4 million	16

In Tab. 1, simulation 5 is marked with an asterisk to indicate that it is different from simulation 1, because of the different geometry due to the introduction of a mini-fan, as discussed in the following. In each simulation, both the hood deposition period (10 min) and the FID operation period (2 min) were simulated, in order to verify the effects that suction produces on the system during the analysis.

In simulation 1, the hood was simulated according to the first design proposed - i.e. 0.10 m high - and the LFG flow was set equal to 0.25 $l/m^2/h$. This flow value was chosen based on the values obtained in previous similar works (Palmiotto et al., 2014; Lucernoni et al., 2015) investigating landfills in northern and central Italy similar to the site here considered. This simulation aims to validate the two hypotheses on which Eq. 3 relies for the estimation of the LFG emission rate from the CH_4 concentration measured inside the sampling hood: i) the linear growth of CH_4 concentration during the first 10 min of deposition time, and ii) the representativeness of the sampling point, i.e., the assumption that the value read with the FID is representative of the average concentration inside the hood. It is important to highlight that for all the simulations a first improvement of the hood design was introduced by moving the 3m-long open tube from the lateral to the top of the chamber in order to prevent perturbations on the developing concentration front that might deviate due to the lateral opening.

Once this first hypotheses were proven, it was deemed interesting to further investigate the position of the optimal sampling point, i.e. the point in which the methane concentration is equal to the average methane concentration inside the hood, for different sampling conditions.

For this reason, different variables were examined by simulating the methane concentration variation inside the hood in modified conditions, in order to verify and prove whether or not the outcomes of the first simulation can be generalized to different field situations (Lucernoni et al., 2015).

First, the LFG flow rate was modified from the first attempt value of 0.25 $l/m^2/h$, to a significantly lower value of 0.05 $l/m^2/h$ (simulation 2) and to a significantly higher value is of 1 $l/m^2/h$ (simulation 3), by keeping the hood features constant. The flow rate values were chosen as to remain within the validity

boundaries of the considered fluid dynamic regime, which is the laminar diffusive regime, and thus within the boundaries set by the ANSYS Fluent software in terms of cell dimensions, Courant number, etc. Those values are also representative of the limits for LFG emissions from landfill surfaces, typically observed in the field, for northern Italian MSW landfills.

Then, the hood volume was modified by changing its height from 10 cm to 20 cm (simulation 4).

Simulation 5 was set up in order to investigate possible modifications and improvements to the proposed hood design based on the outcomes of the previous simulations. One main aspect that was considered is the homogenisation of the CH_4 concentration inside the hood before the FID operation, which could be improved by the introduction of a fan, thus giving a sampling procedure less sensitive to the sampling point. The fan was located in the top left corner of the chamber, with a 2.5 cm diameter, spinning at a speed of about 400 rev/min.

For all simulations, it was set an air temperature of 17°C and a soil temperature of 16°C, representative of the situation in the field.

4. RESULTS AND DISCUSSION

4.1 SIMULATIONS RESULTS – FIRST HOOD DESIGN

In order to verify linearity of the CH_4 concentration, the CH_4 concentration was monitored with Fluent at the top of the chamber (i.e. at the inlet of the FID sampling tube), for the 10 min deposition period.

The obtained values were linearly interpolated, providing a satisfactory R^2 correlation index of 0.9994, thus validating the initial hypothesis. Fig. 3 shows the obtained plot for the trend and the corresponding table with the numerical values of the concentration, allowing to visually appreciate this evidence. Moreover, in Fig. 3 also the mean CH_4 concentration in the hood at each minute is reported. This can be evaluated by means of a material balance on the hood that – for the considered situation – can be written as shown in Eq. (4).

$$c_{CH_4}^{mean}(t_i) = \frac{q_{LFG} * x_{CH_4}^{LFG}}{3600} * \frac{S_{hood}}{V_{hood}} * (t_i) * (10^6) = \frac{2.5}{7.2} * (t_i) \quad (4)$$

Where ($c_{CH_4}^{mean}$) is the mean methane concentration in the hood at time (t_i) in [ppm], (q_{LFG}) is the specific LFG flow rate entering the chamber in [l/m^2/h], ($x_{CH_4}^{LFG}$) is the methane molar fraction in the LFG, (S_{hood}) is the base area of the hood in [m^2], (V_{hood}) is the volume of the hood in [l], (t_i) is the time elapsed in [s].

OUTLET		MEAN
t [s]	c,CH_4 Fluent [ppm]	c,CH_4 mb [ppm]
60	11	21
120	29	42
180	48	43
240	66	83
300	86	104
360	105	125
420	125	146
480	145	167
540	166	188
600	187	208

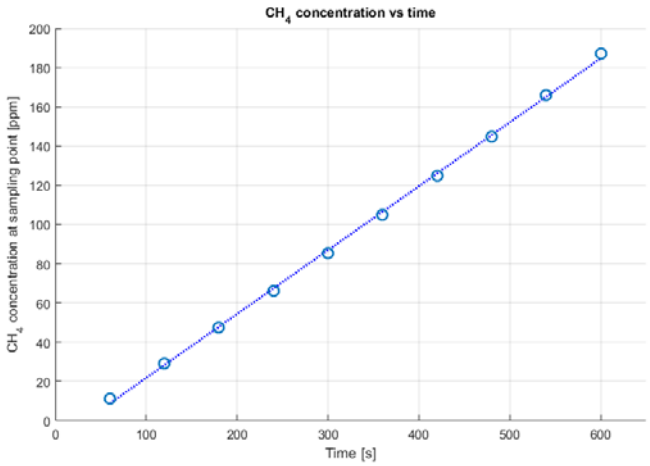


Figure 3 CH_4 concentration trend at the FID sampling tube inlet.

In Fig. 3, the tabulated methane concentration values are those obtained from the software at the sampling point and those computed as shown in Eq. (4). Comparing them, it is possible to notice how the % discrepancy decreases as time increases, i.e. after 10 min the outlet concentration is representative of the mean value in the hood.

The second hypothesis verified with this CFD simulation is the assumption that the collected sample with the FID has a concentration representative of the average concentration in the entire hood volume.

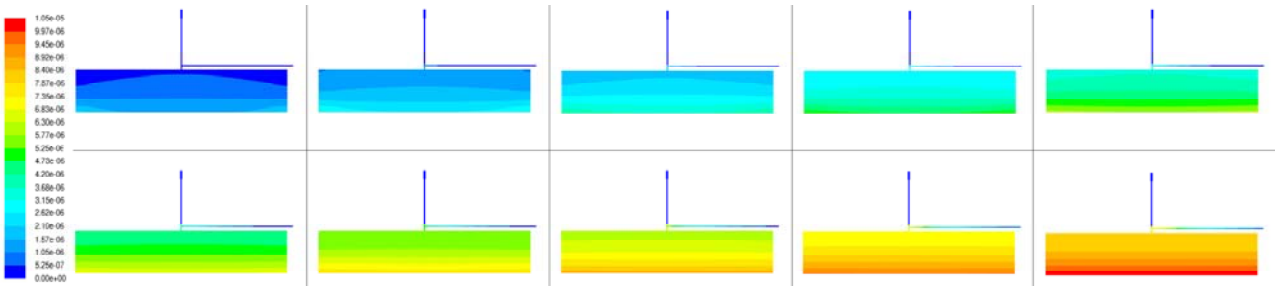


Figure 4 CH_4 concentration profile in [kmol/m^3] inside the chamber during the 10 min deposition time.

As it is possible to appreciate in Fig. 4, during the 10 min deposition period the CH_4 stratifies in the internal volume, with concentration decreasing with height. Such behaviour is due to the nature of the mass transfer phenomenon, which is purely diffusive. This aspect can be better understood considering that the diffusive velocity in the hood is about 10^{-4} m/s, while the convective velocity is about 10^{-7} m/s, which can be computed as shown in Eq. (5)-(6).

$$v_{diff} \cong \frac{\wp_{mix}}{h} \tag{5}$$

$$v_{conv} \cong \frac{\hat{Q}_{LFG}}{S_h} \tag{6}$$

Where (v_{diff}) is the diffusive velocity in [m/s], ($\wp_{mix}$) is the mixture diffusivity equal to 10^{-5} [m^2/s], (h) is the hood height in [m], (v_{conv}) is the convective velocity in [m/s], ($\hat{Q}_{LFG}$) is the LFG emission flux [m^3/s], (S_h) is the hood base area in [m^2].

Looking at the shape of the concentration profile (Fig. 4), it is possible to notice that in the early moments it assumes a lanceolate pattern, then becoming flat in the following. In order to explain this behaviour, an investigation was performed concerning the velocity vectors in the chamber. In Fig. 5, the velocity vectors in the vertical direction are depicted, after 1 min and after 10 min of hood deposition time.

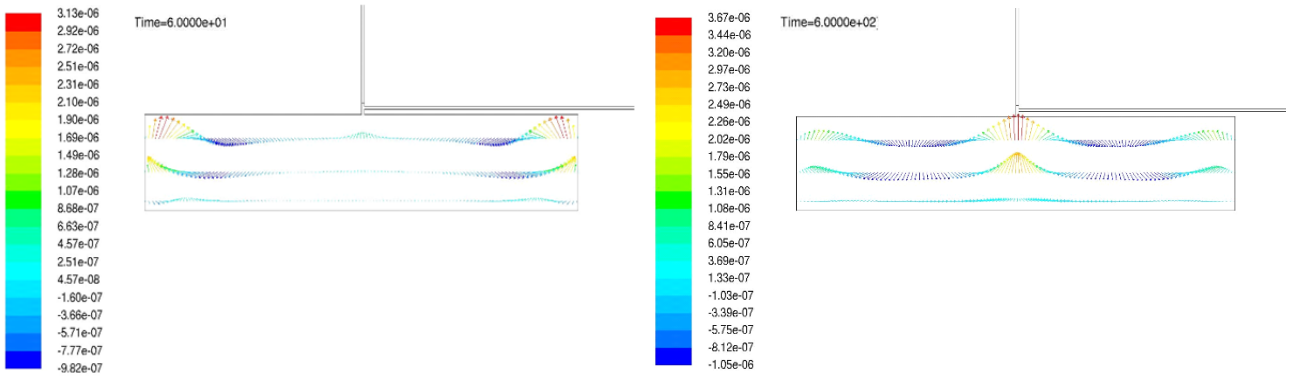


Figure 5 Vertical (y-direction) velocity vectors after 1 min (left) and after 10 min (right) of hood deposition time.

Looking at Fig. 5 it is possible to see how after 1 min the velocity zeroes at the walls but has maximum intensity in the top corners near the walls, while flattening towards the centre of the hood. This indicates that there are recirculation phenomena in the upper part of the chamber – even though the modules of the velocity are almost negligible – and that there is a "chimney effect" caused by the tube on the top wall. On the contrary, after 10 min the situation is reversed, with the higher intensity located at the central pipe inlet (i.e. sampling point), while the velocity vectors near the walls are very small, indicating that there is no more recirculation in the corners of the chamber.

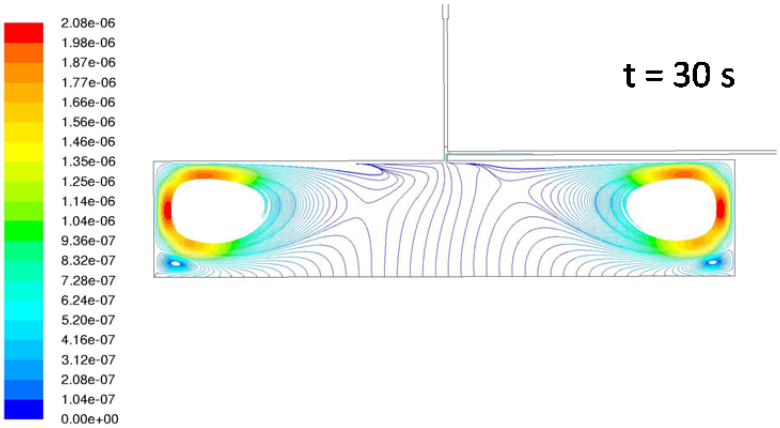


Figure 6 The velocity path-lines at 30 s of hood deposition time.

Fig. 6 shows the velocity path-lines after 30 s of hood deposition time. Such behavior can be explained since in the initial times the CH_4 concentration in the hood is low, thus the convection is the controlling phenomenon, and therefore the effect of the walls and the top tube produces the swirls in the top corners with negative (downward) velocities. This causes an accumulation of CH_4 in the lower corners and gives the peculiar lanceolate shape to the concentration profile. Then, when CH_4 concentration increases, the

diffusion becomes dominant “evening up” these effects and producing the flat concentration profile. As discussed in the next paragraphs, this evolution is observed in all situations.

Both Fig. 5 and Fig. 6 show that it is possible to have unexpected situations inside the sampling hood during the initial moments whereby sampling would be critical. This is due to the procedure required to position the hood on the soil, which may produce pressure and temperature differences that cause unexpected behaviors inside the chamber. For the case at hand, it was found that a time of 10 minutes is required to dampen the significance of these phenomena and obtain a representative result.

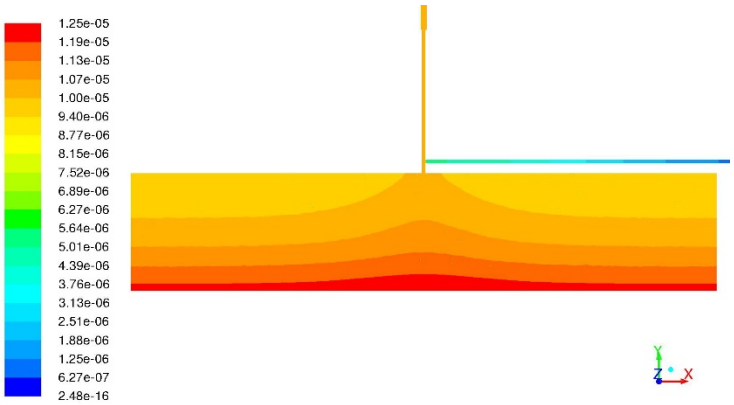


Figure 7 CH_4 concentration profile in [kmol/m^3] after the 2 min FID measure period.

As stated, after the simulation of the firs 10 min, the FID operation was simulated. Looking at Fig. 7, it is possible to see that after the FID operation, the system sustains a perturbation: the system results no longer completely segregated. The CH_4 is distributed more uniformly in the volume. Comparing the concentration values at the sampling tube inlet (242 ppm or 1.02 kmol/m^3) and the average one (250 ppm or 1.05 kmol/m^3), at the end of the 2 min FID operation, it is confirmed that the chosen sampling point is even more representative.

The concentration values are all reported in Tab. 2, for all simulations, at end of the hood deposition time and at the end of the FID operation. It is worth remarking that the values reported in Tab. 2 refer to the concentrations extrapolated from Fluent.

Looking now at Fig. 4, at the end of the 10 min deposition period, which is the height where the punctual concentration value is exactly equal to the average, it is possible to see that this point is roughly at 4 cm

from the ground, i.e. at about 40% of the chamber height. The position where the concentration inside the hood is equal to the mean was checked also in the following simulations performed, in order to prove whether or not this situation is purely casual or it is a constant also in different situations.

4.2 SIMULATIONS RESULTS – DIFFERENT CONFIGURATIONS

4.2.1 DIFFERENT SOURCE CONFIGURATIONS

A comparison was carried out among three different situations, with different values of LFG emission flux, for a fixed hood height and volume: standard situation (simulation 1), low emission (simulation 2), high emission (simulation 3) (see par. 3.3).

The CH_4 concentration profile inside the hood, for simulations 2 and 3, at the end of the 10 min deposition period is depicted in Fig. 8, left and right respectively:

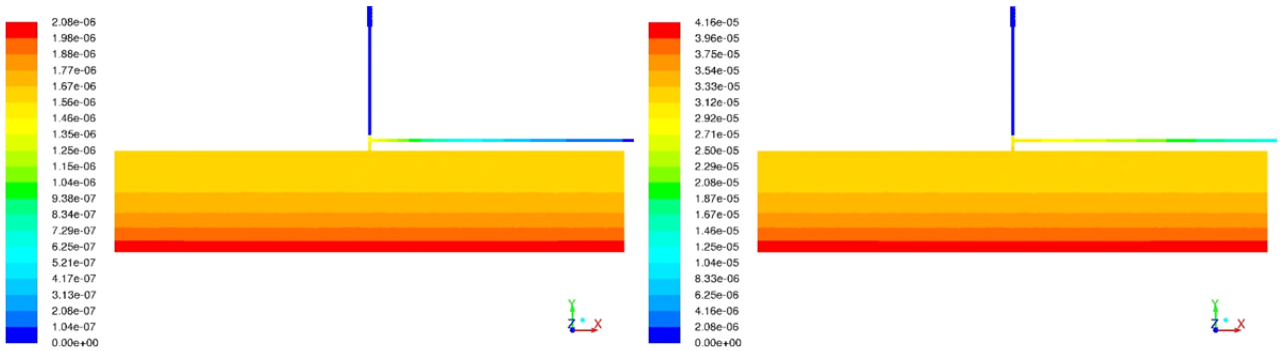


Figure 8 CH_4 concentration profile in [kmol/m^3] after the 10 min deposition period, low (left) and high LFG emission (right).

The pictures in Fig. 8 look identical, but since the LFG flow rates differ of a factor 20, also the concentration scales differ of a factor 20, i.e. the concentrations in the bottom are much higher than the ones in the top.

Moreover, Fig. 8 shows that the CH_4 concentration is stratified inside the chamber as it was in the previous configuration. With lower flow rates – thus lower convective velocities – the time required to reach the stationary regime is greater.

Now, looking at the mean CH_4 concentration in the hood at the end of the 10 min deposition time and the concentration at the sampling point, as reported in Tab. 2, it is possible to see that in both cases of low and high emission, the values are comparable, thus confirming the appropriateness of the sampling point.

BEFORE FID	Simulation 1	Simulation 2	Simulation 3	Simulation 4	Simulation 5
c,ave [ppm]	209	42	831	156	208
c,sample [ppm]	187	37	750	120	203
AFTER FID	**Simulation 1**	**Simulation 2**	**Simulation 3**	**Simulation 4**	**Simulation 5**
c,ave [ppm]	250	50	1001	178	250
c,sample [ppm]	242	49	965	147	248

Table 2 Sampling point and average CH_4 concentration, after the 10 min hood deposition period and after the 2 min FID operation.

Similarly to the previous situation, after the 2 min FID operation period, a certain degree of mixing of the system is observed for both configurations, giving that the mean concentration and the concentration at the sampling point are similar, as shown in Tab. 2. The height of the iso-concentration surface corresponding to the average concentration in the chamber is found at about 40-45% of the hood height.

4.2.2 DIFFERENT SAMPLING SYSTEM CONFIGURATION

In this simulation, the hood volume was modified by changing its height from 10 cm to 20 cm.

The CH_4 concentration profile in the hood, at the end of the 10 min deposition period, is depicted in Fig. 9 (left).

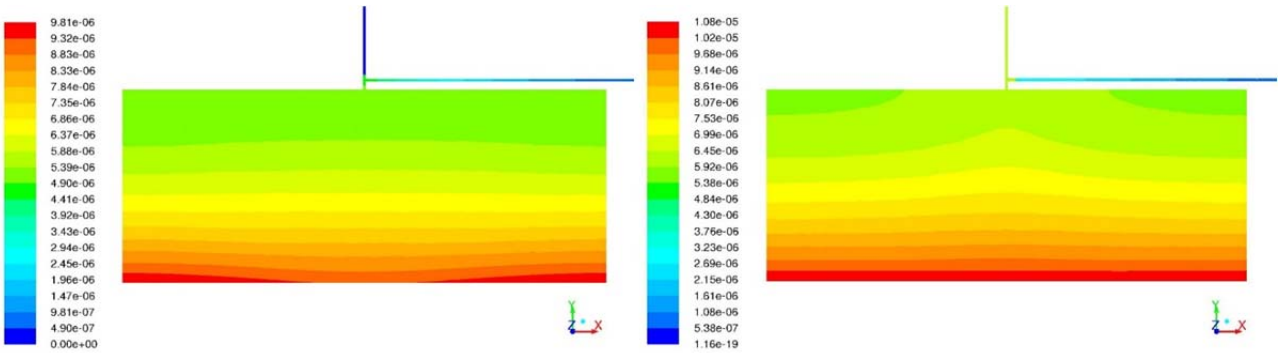


Figure 9 CH_4 concentration profile in [kmol/m^3] inside the chamber, at the end of the 10 min deposition time (left) and after the 2 min FID operation (right).

In this case as well, stratification of the methane concentration is observed, even though the profile results less flat. Referring to the discussion concerning Fig. 4, this is probably because the volume is double and it takes longer for the profile to “even up”.

Similarly to the previous situations, after the 2 min FID operation period, a certain degree of mixing of the system is observed, even if such effect is much less marked in this case, as shown in Fig. 9 (right).

Looking at Tab. 2, it is possible to see that also in this case the mean CH_4 and the value at the sampling point are comparable, both before (i.e. after the 10 min deposition period) and after the sampling (i.e. after the 2 min FID operation period).

Also in this case, it is possible to see that the height at which the concentration is equal to the main value is at about 40-45% of the chamber height.

4.3 DISCUSSION

The simulations presented in the previous sections yielded several interesting results. First, they allowed to validate the hypothesis made concerning the linear growth of the CH_4 concentration in the hood over the first minutes of sampling and the choice of a proper sampling point where the concentration is representative of the mean value inside the chamber, for the case of the first hood design proposed. In addition, it was highlighted that in any case, after the 2 min FID operation, the system results mixed.

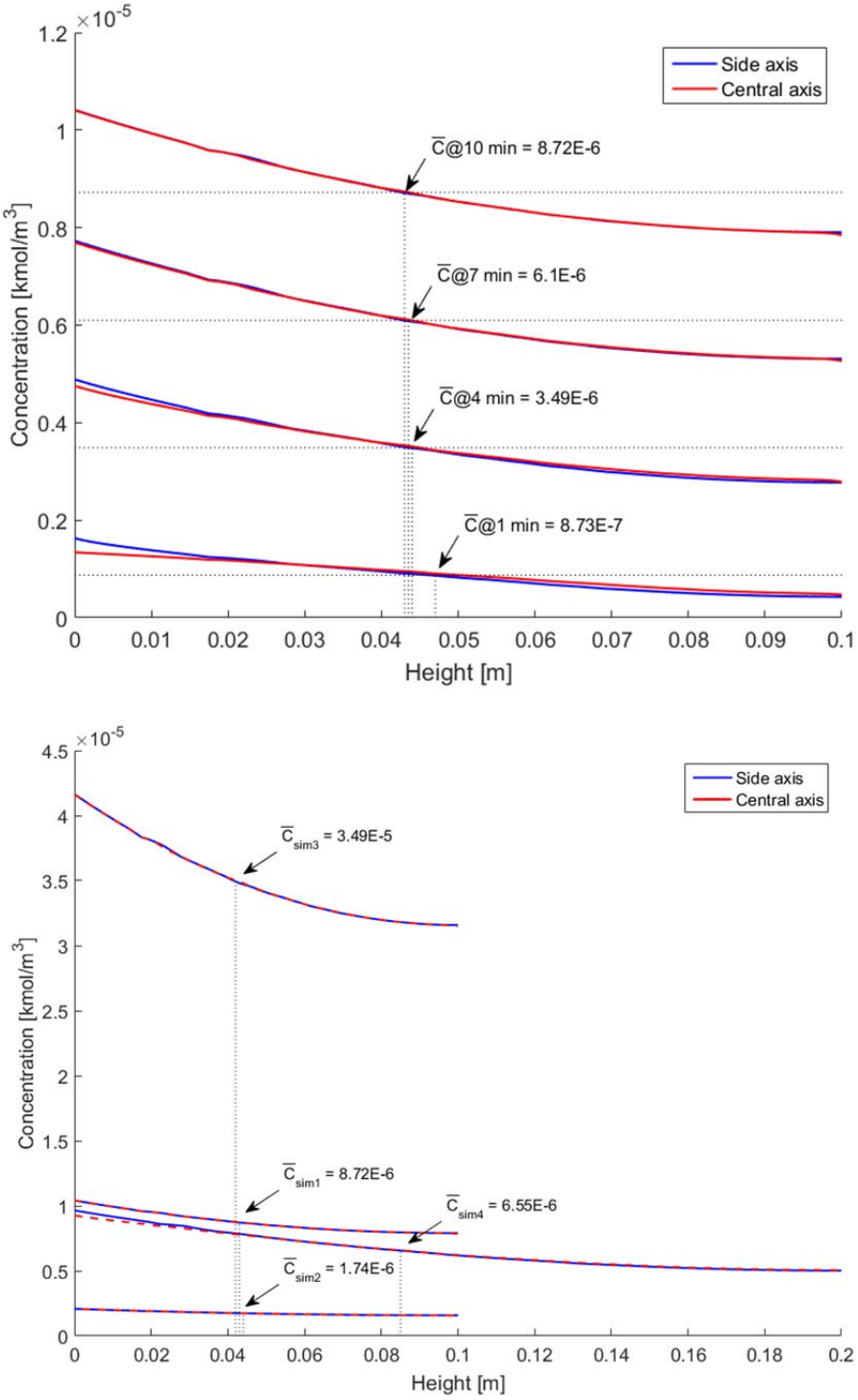
It was possible to see that the height where the concentration iso-surface is the mean value in the hood – averaged on the entire volume – is always at a level above ground roughly equal to the 40-45% of the chamber height. As it is shown in Fig. 10, it is possible to see that in all the considered situations, the methane concentration values on the central axis of the hood the average value is always found at a height slightly lower than 50% of hood height (i.e. 40-45%).

Fig. 10 (top) shows the concentration values for Simulation 1, taken at different times (1, 4, 7, 10 min) and at different heights (from ground to top); the average value is always found at a height slightly lower than 50% of hood height, starting at a value close to 50% (at 1 min) and then settling around 43%.

Fig. 10 (bottom) shows the concentrations for the Simulations 1-4 at the end of the first 10 min: in each case the average concentration is reached around the 40-45% of the hood height.

374 Moreover, in Fig. 10, the methane concentrations are reported for two vertical axis in the hood, one
375 corresponding to the sampling tube axis (central axis), at 0.25 m from the lateral wall and one at a distance
376 of 0.1 m from the lateral wall (side axis).

377 This leads to the conclusion that when operating a sampling hood in a situation similar to the ones
378 considered in the present study, the ideal sampling point should be at a level somewhat lower than 50% of
379 the hood height.



380

381 *Figure 10 CH_4 concentration trends over time and space.*

382 **4.4 SIMULATIONS RESULTS – MODIFIED HOOD DESIGN**

383 Simulation 5 entails the presence of mini-fan that should help in achieving a satisfactory mixing degree
384 inside the chamber also before the FID operation. The mini-fan chosen for the simulation is a Jamicon®
385 KF0210S5MR axial fan, 25x25x10 mm.

The CH_4 concentration profile inside the hood, at the end of the 10 min deposition time, is represented in Fig. 11 (left).

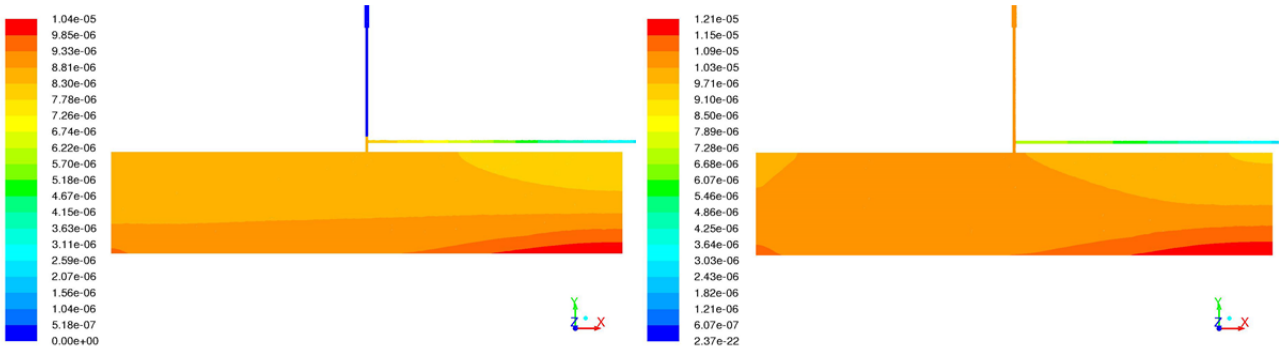


Figure 11 CH_4 concentration profile in [kmol/m^3] after the 10 min deposition period (left) and after the 2 min FID operation (right), with mini-fan.

Looking at Fig. 11 (left), it shows that the introduction of a mini-fan does result in the expected effect – i.e. the achievement of a good mixing degree in the chamber also before the FID operation – in facts the outcome is a fairly uniform concentration in the hood.

In this case, after the 2 min FID operation period, Fig. 11 (right), the situation is not significantly different from the one depicted in Fig. 11 (left), i.e. before FID operation. This indicates that the mini-fan serves well its purpose.

In order to better appreciate the action of the mini fan, Fig.12 shows a different plane inside the chamber.

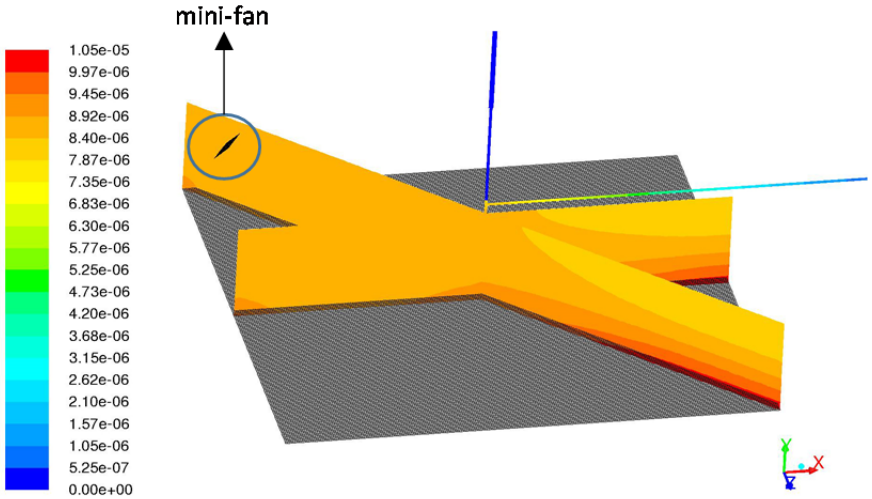


Figure 12 CH_4 concentration profile in [kmol/m^3] after the 10 min deposition period, different angle.

400 In analogy with paragraph 4.2.2, it is possible to observe the CH_4 concentrations (average and at sampling
401 point) both before and after FID operation, the values are shown in Tab.2.

402 **5. CONCLUSIONS**

403 The main goal of the present work was to provide a method for designing a static sampling hood, exploiting
404 CFD simulations. Such method was presented, applied to the specific case of methane concentration
405 measurement on landfill surfaces. However, even though the procedure depicted is specific, the method is
406 to be considered as general: in facts, by considering the peculiarities of the case considered, it can be
407 applied to the optimized design and suitable development of any sampling hood for the assessment of
408 emissions from area sources.

409 This study highlights the main aspects to focus on in order to successfully design an effective sampling
410 device. First, it is necessary to verify the fundamental hypothesis made that allow writing the mass balance
411 for the hood. Then, it is necessary to check whether the system is segregated or mixed, leading to a
412 discussion concerning the optimal position for the sampling point. Finally, it is recommendable to
413 investigate what are possible modifications to the design proposed in the beginning and what such
414 modifications imply in terms of fluid-dynamic behavior of the system inside the chamber.

415 The project proved that CFD could be effectively applied for designing specific static sampling devices for
416 area sources; moreover, it showed CFD to be a valuable asset for this task.

417 Referring to the analyzed situation of LFG emissions from landfill surfaces, the simulations performed
418 yielded several interesting outcomes.

419 First, they verified that CH_4 concentration grows linearly over time inside the hood, in the first 10-15
420 minutes, allowing to write the mass balance for the chamber according to Eq.3. Moreover, it was shown
421 that the FID operation provides a certain degree of mixing to the system, thus increasing the reliability of
422 the measured data, since the sampled gas is likely to have a CH_4 concentration very close to the average,
423 making the measurement representative of the general condition.

It was also proved that the sampling point should be always at a height above ground about 40% of the hood's height, since this is where the concentration value is almost equal to the average concentration value inside the hood. This statement holds true even as both the dimensions of the hood and the intensity of the LFG emission vary.

The simulations also suggested a possible improvement for the design: introducing a mini-fan inside the hood to achieve mixing also before turning on the FID. The modification turned out to be actually an improvement: the introduction of a mini-fan affects the system, providing a satisfactory mixing degree also before FID operation, as it is possible to see the situation before and after FID operation is fairly similar (see Fig. 11).

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