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To cite this version:

Zbigniew Pokryszka, Christian Tauziède, Philippe Cassini. Development and validation of a method for measuring biogas emissions using a dynamic chamber. 5. International Landfill Symposium "Regulation environmental impact & afftercare" (Sardinia'95), Oct 1995, Margherita di Pula, Italy. pp.495-506, 1995. <ineris-00971947>

HAL Id: ineris-00971947
https://hal-ineris.ccsd.cnrs.fr/ineris-00971947
Submitted on 3 Apr 2014

5th International Landfills Conference - Sardinia'95, Cagliari, 1995

DEVELOPMENT AND VALIDATION OF A METHOD FOR MEASURING BIOGAS EMISSIONS USING A DYNAMIC CHAMBER

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Abstract: Since 1990, INERIS carried out research on the measurement of surface biogas flow, designing a dynamic flux chamber. Preliminary bench tests revealed the necessity of defining the corrective factors required to ascertain the actual flow rate from the measured value. Measurements performed on an actual MSW landfill confirmed the performance of the method defined in the laboratory, as well as the extremely high spatial heterogeneity of methane emission on this landfill.

1. INTRODUCTION

The landfilling of waste is likely to put into the environment polluting or malodorous substances, a large part of which is released in the form of gas. Among the different types of landfills, it is MSW that emits the most intense gas releases.

A mixture of gases (known as biogas) is produced from organic waste, and consists mainly of methane, carbon dioxide and other gases in much lesser quantities.

The consequences of biogas release are extremely diverse, but the following are the major consequences recognized at the present time (see Figure 1):

- The risk of explosible mixtures which can migrate to urban areas

Hundreds of accidents (i.e. explosions) or incidents arising from migrating biogas have occurred and been reported (Rees, 1980; Parker, 1986; Gendebien et al., 1992).

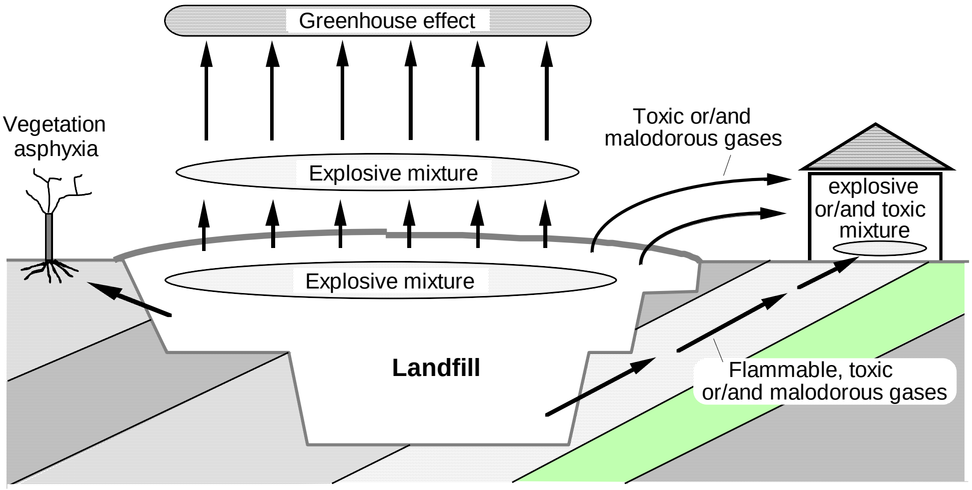

Figure 1. Some forms of potential impact of biogas emissions from landfill

- Drift of noxious gases and unpleasant smells

  Waste dumps (including MSW landfills) often release toxic or malodorous gases which can affect urban areas (Gendebien et al., 1992).

- Greenhouse Effect

  The ratio of the landfill released methane to the global released methane (one of the main causes of the Greenhouse Effect) ranks, according to one or another estimation, from 5% to 25% in France and at approximately 20% throughout the world.

Having regard to the consequences described above and the potential dangers arising from biogas output, it is essential to have a system and a procedure enabling gas release to be defined and quantified, for the following purposes:

- to meet international obligations in respect of the inventory and prevention of gas causing the greenhouse effect;
- to ascertain by on-site tests the best suited treatment and landfilling methods in order to reduce gas emission;
- to define the decisions required in order to implement the techniques necessary to reduce and prevent gas emission;
- to design a system for assessing the effectiveness of the above techniques;
- lastly, to detect and evaluate risks arising from gaseous emissions such as, for example, the drift of pollutants and flammable gases.

Thus the aim of the research carried out by INERIS, under the project financed by the Ministry of the Environment, was to develop a simple and reliable way of measuring the emission of gas from the surface of a landfill (Pokryszka, 1993).

2. SELECTION OF MEASURING METHOD

The available literature contains a number of methods designed to measure surface gas flow rates, and indeed has been reviewed in order to weigh up their various advantages and disadvantages. Following this, it was decided to orient the research in the direction of localized gas flow measurement using a dynamic chamber.

The usefulness of this type of technique is twofold: first, it allows direct measurement not dependent on hypotheses in respect of the emission and dispersion of gas into the atmosphere; secondly, it can be carried out in a wider range of gas concentration, which greatly facilitates the operation. This method and its application are often to be found in the relevant literature (Denmead, 1979; Jury et al. 1982, Christensen, 1983; Hunsted, 1993).

The chief advantages emphasized by the authors are the simplicity of the system, the ability to detect minimal gas flow leaks, reliability of measurements and the fact that the system can be used in adverse meteorological or topographical conditions. The main drawback is modification of the gas flow in the field and of gas exchange at the earth-air interface (Mosier, 1990).

The approach adopted in the end for future development was a flux dynamic chamber.

3. WORKING PRINCIPLE OF THE FLUX CHAMBER

The method of measuring biogas emissions by using a dynamic chamber is a direct method and consists (see Figure 2) of the following:

- Covering an area as hermetically as possible, without altering the environment. The shape of the area covered should be elongated and the height of the enclosed volume should be minimal.
- Getting a sweep gas flow (inert gas) in the measuring chamber by injection at one end "e" (entry). The sweeping flow rate should be distinctly higher than the rate of gas release in the covered area.
- Passive collection and measurement of the sweep gas/biogas mixture at the other end "s" (exit) of the chamber.
- Follow-up of the concentration of biogas constituents in the collected gas.

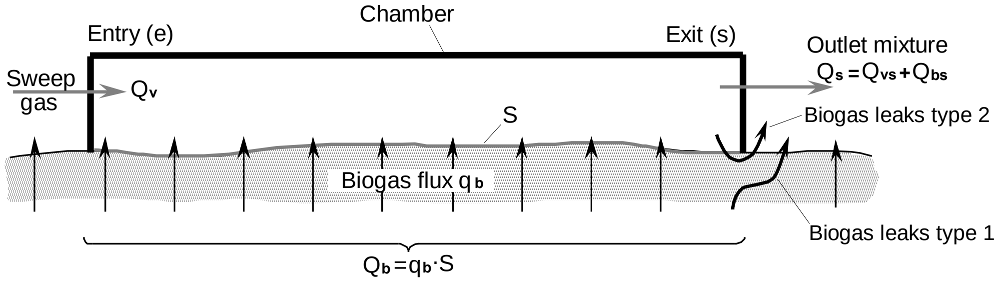

Figure 2. Principe of biogas flow measurement by means of the dynamic flux chamber

On the basis of the parameters measured and given an analytical model, the flow of biogas from the chamber and thus the flow rate emitted by the covered area can be determined.

3.1 Symbols

S	Surface area covered, (m^2)
Q_v	Flow rate of sweep gas injected into the chamber, (Nl/min)
Q_{vs}	Flow rate of sweep gas coming out of the chamber, (Nl/min)
Q_{vf}	Leak rate of sweep gas, (Nl/min)
K_v	Recovery rate of sweep gas, (adimensional)
Q_b	Actual flow rate of biogas emitted by the area covered, (Nl/min)
q_b	Actual flow rate of biogas emitted per square metre of covered area "S", (Nml/min/m^2)
Q_{bs}	Flow rate of biogas coming out of the chamber, (Nml/min)
Q_{bf1}	Flow rate of type 1 leak concerning the biogas coming out of the ground ,(Nml/min)
Q_{bf2}	Flow rate of type 2 leak concerning the biogas coming out of the chamber, (Nml/min)
K_b	Recovery rate of biogas, (adimensional)
Q_s	Flow rate of biogas/sweep gas mixture coming out of the chamber, (Nl/min)
$C_{bs}(i)$	Concentration of biogas constituent i in the gas coming out of the chamber, (adimensional)
$q_b(i)$	Flow rate of biogas constituent i per square metre of the surface area S, (Nml/min/m^2)

3.2 Choice of Analytical Model

Figure 2 shows the gas flows into and out of the system. The flow of biogas coming out of the chamber is calculated using the formula below by measuring the value Q_s and the concentration of the biogas constituents:

$$Q_{bs} = Q_s \sum_{i=1}^{n} C_{bs}(i) \qquad (1)$$

The Q_{bs} value determined by Formula 1 above represents only a part of the biogas released from the surface area S. This part equals the total biogas emission Q_b from the surface S, reduced by the leak rate, as follows:

$$Q_{bs} < Q_b \qquad (2)$$

Leaks result from two causes:

- The presence of the chamber affects gas flow in the ground and gas exchange with the free air. Part of the gas, usually emitted by the surface area S, does not enter the chamber but migrates laterally (Type 1 leaks, flow rate Q_{bf1}).
- The system is not completely leak proof, so some of the gas coming into the chamber escapes in the same way as the sweep gas (Type 2 leaks, flow rate Q_{bf2}).

To express the mass conservation equation in respect of biogas, we obtain the following:

$$Q_b = Q_{bs} + Q_{bf1} + Q_{bf2} \qquad (3)$$

Unfortunately, this equation does not enable the actual unaffected biogas flow rate Q_b to be determined as the leak rate is unknown and difficult (not to say impossible) to measure or evaluate by a simple method.

If the aim is to get an analytical model and a measuring procedure relatively simple, a number of simplifying hypotheses need to be applied. Thus on the supposition that the total leak flow rate of biogas is approximately proportional to the Q_b biogas emitted, and remains constant for measurements performed under conditions that remain identical, the biogas recovery rate can be expressed as follows:

$$K_b = \frac{Q_{bs}}{Q_b} \qquad (4)$$

From (1) and (4) we obtain the following:

$$Q_b = \frac{Q_s}{K_b} \sum_{i=1}^{n} C_{bs}(i) \qquad (5)$$

If we reduce this to surface S, we obtain the flow rate of biogas per square metre:

$$q_b = \frac{Q_b}{S} \qquad (6)$$

Thus:

$$q_b = \frac{Q_s}{K_b \cdot S} \sum_{i=1}^{n} C_{bs}(i) \qquad (7)$$

If one takes into account only one of the constituents, its emission flow rate per square metre is given by the following formula:

$$q_b(i) = \frac{Q_s}{K_b \cdot S} C_{bs}(i) \qquad (8)$$

So we can determine the required Q_b value on the basis of Q_s and the $C_{bs}(i)$ concentrations, provided we know the recovery rate of the biogas K_b.

The K_b value, i.e the relationship between the measured biogas collected flow rate and the actual emitted flow rate results from both the way in which the measuring equipment influences the biogas emission and in a certain way the tightness of the measuring chamber. So it can vary according to the operating parameters of the method (chamber construction, flow rate and speed of the sweep gas, and so on) and the "natural" conditions (type of ground, permeability, biogas emission flow rate, etc.)

4. DEVELOPMENT OF METHODOLOGY

As indicated above, installing a chamber affects gas exchanges between the ground and the air, which by their very nature are characterized by very low pressure gradients. This situation can give rise to measurements that are not entirely accurate. The degree of inaccuracy is initially unknown.

As a result, it was necessary first of all to validate the method designed in the laboratory and in situ. The chief purpose of this was to define the corrective factor(s) to apply in order to compensate for the effect of measuring on the measured value.

Thus in terms of the methodology applied, work was divided into three phases, as follows:

- constructing the chamber and defining the operational parameters;
- adjustment and validation of the method on a laboratory test bench;
- lastly, final adjustment by *in situ* measurements.

5. CONSTRUCTION OF THE CHAMBER

The initial phase consisted of constructing the chamber and determining the operational parameters (see Figure 3).

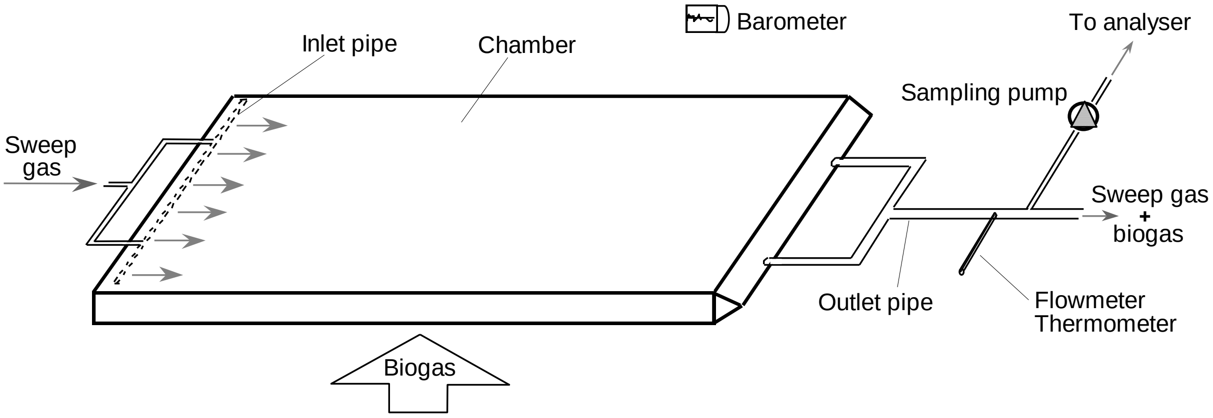

Figure 3. INERIS dynamic flux chamber diagram

Thus the measuring chamber is made up of a plastic film held at approximately 10 cm from the surface of the ground by rigid supports. It is in the shape of a rectangle 5 metres long and 1 metre wide. The impermeability of the chamber on the ground is ensured by a strip of moist sand or clay.

Injection of the sweep gas is done by a feed system consisting of a perforated pipe designed such that the gas is distributed evenly on the whole width of one small side of the chamber. When it leaves the chamber, the gas is collected by two 40-mm tubes which converge into a single pipe.

The flow rate of the sweep gas/biogas mixture coming out of the chamber is determined on the basis of the speed measured by a hot-wire anemometer in the outlet pipe. During validation tests, this flow rate was measured very accurately using helium tracing.

Samples of gas coming from the chamber required in order to analyze its composition are taken from an opening located at the end of the outlet pipe, using a suction pump.

6. VALIDATION OF MEASURING METHOD

6.1 Design of Test Bench

In order to test the method, a test bench ensuring a well-regulated gas emission was designed and built such as to represent emission under actual conditions. It consists of a layer of sand under which a mixture of methane and carbon dioxide flows out (see Figure 4 below).

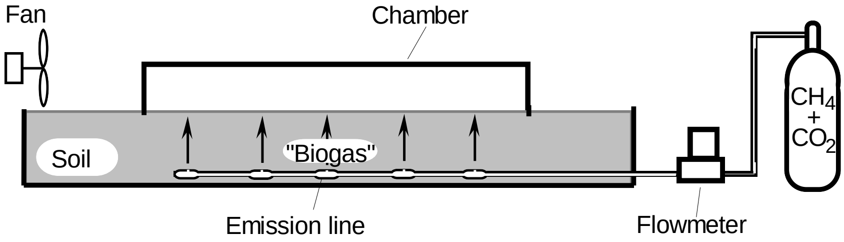

Figure 4. Diagram of test bench for chamber validation

Dimensions are as follows: length 6 metres, width 1.8 metres, height approximately 0.2 metres. The biogas flow is regulated by a mass flowmeter and distributed under the test bench by numerous uniformly perforated hoses. Near the test bench there is a fan designed to create locally draughts simulating normal wind.

6.2 Parameters

During tests, we varied the following parameters:

- Q_v sweep gas flow rate: 10.2 Nl/min to 91.8 Nl/min by increments of 10.2 Nl/min
- Biogas emission: 4 surface flow values - 71, 7.1, 0.71 and 0.071 Nml/min/m^2
- Ground permeability, including water and compaction. Three types of ground were examined: highly permeable (dry sand); moderately permeable (moist sand); and fairly impermeable (compacted and water-saturated sand).
- Side wind: measures were taken on a wind ranging from 0 to 4.5 m/s.

6.3 Results

Testing the method on the test bench confirmed that the method used affects gas emission regardless of the precautions taken. The ratio between the actual emission and the emission observed in the chamber can in extreme cases reach values of 3 to 4.

The rate of biogas recovery K_b varied within a range of 0.3 to 0.95 depending on measuring conditions. Experiments have shown that this parameter required in order to determine the biogas emission rate depends simultaneously on the sweep gas rate Q_v and ground permeability. Whilst the

Q_v value is constant and known when measurements are in progress, the permeability of a landfill cover is unknown, and technically hard to determine. Additionally, the permeability value can vary considerably over the surface examined. Thus it is beforehand impossible to establish a relationship enabling the determination of the K_b on the basis of the Q_v value and ground permeability.

Numerous complementary experiments conducted on the test bench have enabled us to resolve this problem.

First, experiments confirmed the hypotheses established when the analytical model was defined. More particularly, they showed that biogas leaks were approximately proportional to the biogas emission rate Q_b and constant (relatively) for measurements performed under identical conditions (see Figure 5).

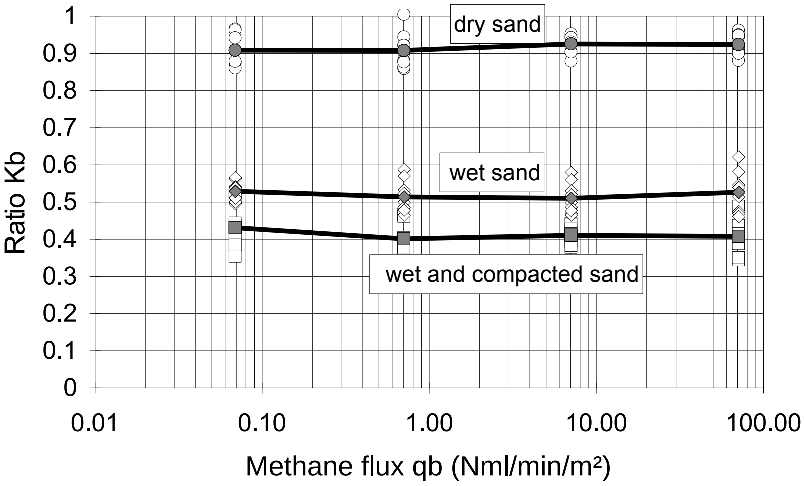

Figure 5. Relationship between ratio K_b and methane flux

Secondly, we were able to identify an auxiliary parameter: the recovery rate of sweep gas K_v, defined as follows:

$$K_v = \frac{Q_{vs}}{Q_v} \tag{9}$$

By definition, the K_v value is constant for a given measurement configuration. Since $Q_{bs} << Q_{vs}$, the value can be determined on a practical basis by the following formula:

$$K_v = \frac{Q_s}{Q_v} \tag{10}$$

Thirdly, it has been shown that K_v depends, rather like K_b, on the sweep gas flow rate Q_v and ground permeability.

This justified looking into the possibility of a statistical relationship between values K_b and K_v. And in fact the existence of this relationship was very clearly confirmed by a non-linear regression calculation on the basis of some 90 measuring points. One of the best correlations ($r^2 = 0.98$) was obtained by the function shown in Figure 6.

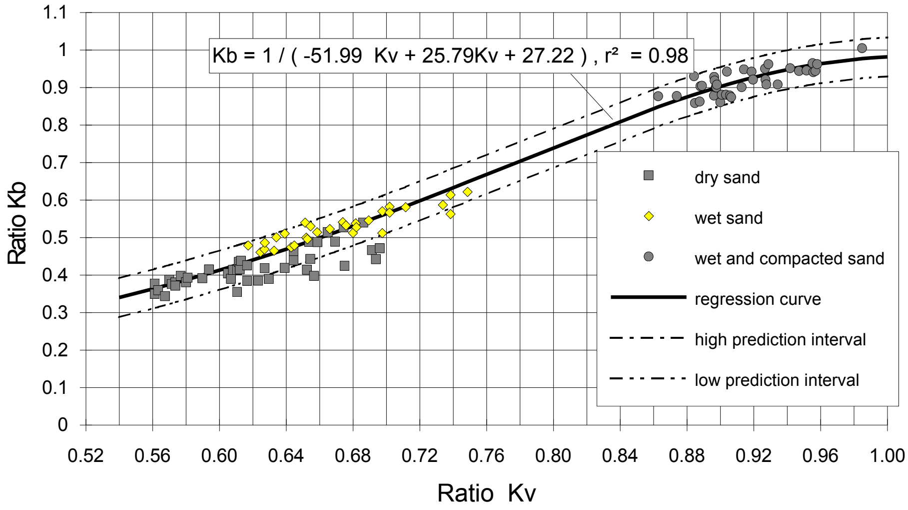

Figure 6. Experimental relationship between ratio K_b and ratio K_v

A relatively low dispersion of the values around the regression curve enabled us to establish prediction limits not far from this curve. The confidence level retained in order to establish prediction limits is $(1 - \alpha) = 95\%$.

The relation found can be used to determine the unknown value of K_b, which is required for working out the biogas emission rate (see formulae 7 and 8 above) on the basis of the K_v value, which can be measured. This means that it is not necessary to know the dump cover permeability value. The uncertainty margin of a value obtained for K_b is defined by the limits of prediction.

This solution has been confirmed and validated by several reliability and repeatability tests carried out in very varied configurations (cf. § 6.2). Figure 7 shows a comparison between actual methane emission rate and collected methane measured during different reliability tests. The dispersion of values around an ideal solution is very low. It never exceeds a theoretical maximum error limit estimated at 15%. This proves the reliability of the method and the relevance of the analytical model used.

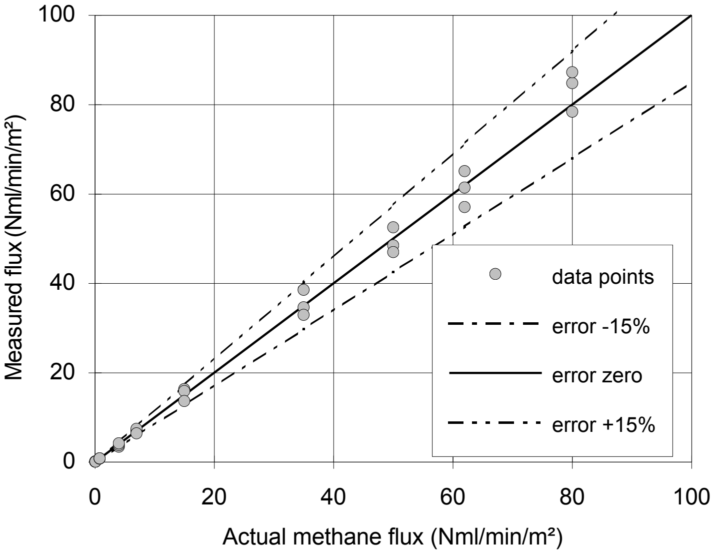

Figure 7. Laboratory results of method reliability test

The repeated tests carried out in the same conditions of ground, biogas emission and injection of sweep gas made it possible to examine the repeatability of the measures obtained by the method. The dispersion coefficients of the results obtained under similar conditions were of the order of 3%, thus the method does, under laboratory conditions, ensure a very good measurement repeatability rate.

The numerous tests conducted have also made it possible to determine the optimum operating parameters in respect of the conditions governing the method used. For example, they showed that, thanks to a relatively large sweep gas flow, the method gives appropriate results up to a wind speed of 4.5m/s.

7. VALIDATION OF THE METHOD *IN SITU*

7.1 Landfill Characteristics

Measures were taken on a specific MSW landfill located in a former clay quarry covering an area of some 3 hectares. The waste (basically MSW) was deposited between 1978 and 1990 to a depth of 4 to 8 metres. Over the entire area, the refuse was covered by a layer of sandy soil well compacted in places. The thickness of the coverage goes from 0.8 to 2 metres. The landfill is not equipped with a biogas drainage system.

7.2 Measuring Points and Tests Carried Out

Tests initially involved an area of 125m^2. Measuring points were spaced regularly over the area at a grid of 25 x 25 metres (Figure 8).

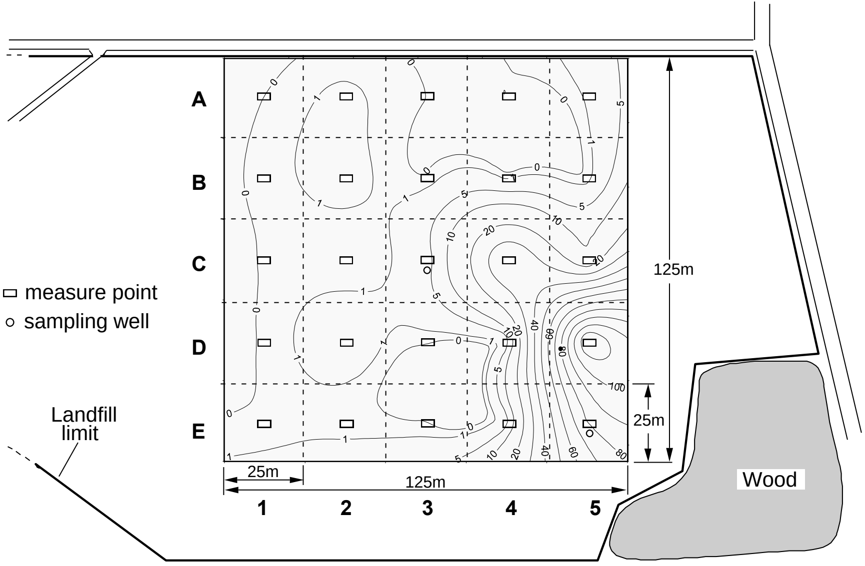

Figure 8. Position of measuring points on the examinated landfill

One of the main part of experiments was to examine in situ operational relationships and parameters of the method created in virtual laboratory conditions, thus reliability and repeatability tests were carried out.

7.3 Results of Validation of *In Situ* Method

To confirm the validity of the analytical model *in situ*, a reliability test was carried out. This consisted of determining the emission of methane at the same point a number of times, always applying different working parameters.

For each chamber site, four sweep gas flow rates were examined (40, 60, 80 and approximately 100 Nl/min) and 3 to 4 measurements were taken for each one, at the following points: C3, C5 and D5 (see Figure 8). It should be noted that these points presented very different methane emission levels (respectively in the order of 3, 10 and 100 Nml/min/m^2). Similarly, the recovery rate of sweep gas measured at these points varied greatly (respectively, in the order of 0.7, 0.5 and 0.9).

Measurement results are shown in Figure 9, together with the methane flow density values observed at given points and in relation to the working parameters examined.

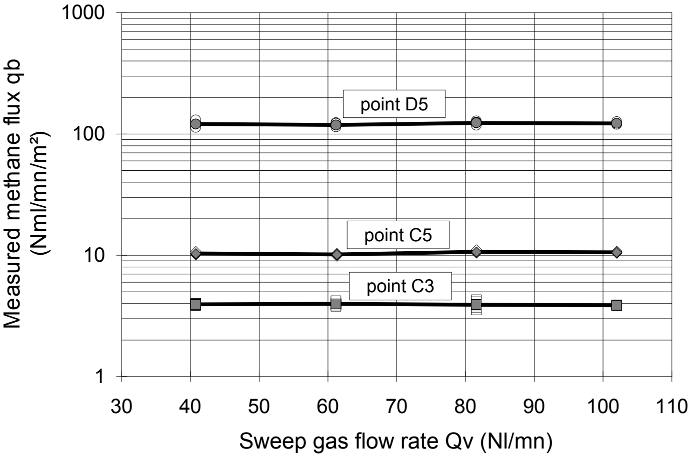

Figure 9. Results of *in situ* validation of the method

These results show that whatever the level of the above values (within the limits laid down for a normal operation), use of the method will always produce the same methane flow density value at any given point. This proves that the analytical model created in the laboratory can be perfectly well applied in the field.

Validation of the method was complemented by a repeatability test, which consisted of repeating a measurement a number of times at the same point (thus in the same ground conditions) and at the same sweep gas flow rate. In order to examine the method in very different configurations, the sweep gas flow rate was modified from one test to another (20.4 to 102 Nl/min). Similarly, the chamber sites selected for test purposes were caracterized by very different biogas emission values (methane flow 0.03 to 125 Nml/min/m^2).

A dozen or so tests of this nature were carried out. These showed (Figure 10) relatively low variability in respect of the results, irrespective of the measuring conditions. Deviations from mean values were less than 8%, thus comparable to those established in laboratory tests. The method ensures good measurement repeatability which is quite sufficient in field conditions.

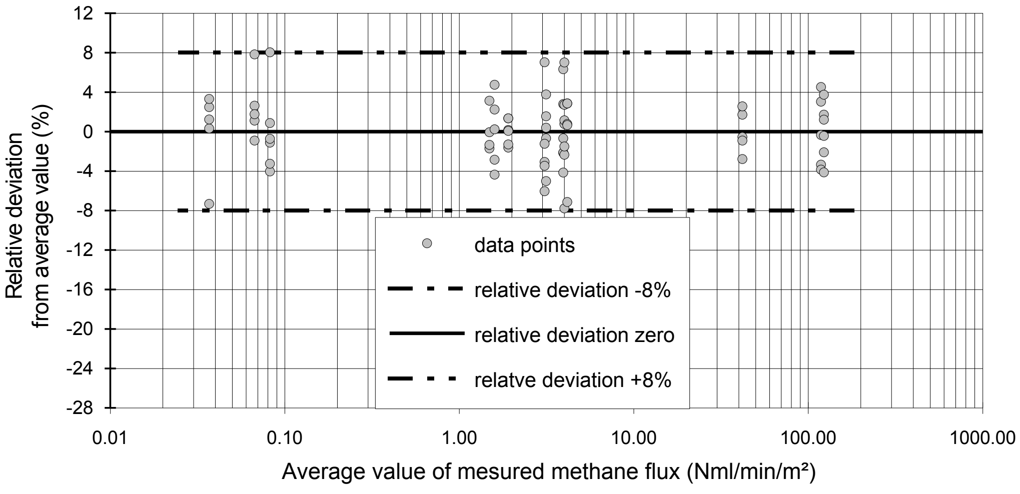

Figure 10. Results of *in situ* repeatability test

8. GASEOUS EMISSONS FROM A MSW LANDFILL

Although in situ experiments have primarily aimed at validating the method, they have at the same time provided concrete information on gaseous emissions from a MSW landfill.

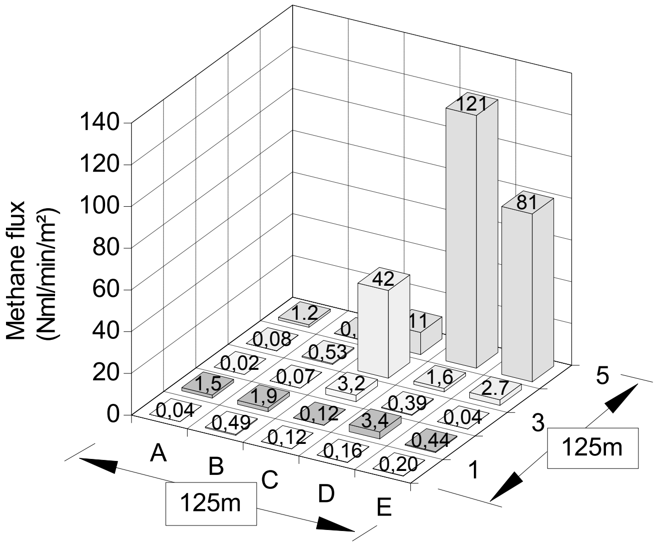

Figure 11. Spatial distribution of methane emission from a investigated landfill

It has been possible among other things to obtain concrete values concerning the emission of biogas from the landfill and to assess the heterogeneity of the emission in both space and time. Methane flow density varied from 0.02 to approximately 130 Nml/min/m^2, which certainly confirmed the extremely heterogeneous nature of emissions of this type (Lifshits and Minko, 1993). A bar graph of the spatial distribution of the methane flow values measured is shown in Figure 11.

In situ experimental results have also made it possible to make an initial attempt to assess the overall emission factors on the basis of localized measurements. For this purpose, we used a special geostatistic method - kriging.

The main advantage of this method is that it can be used to map the flow density (Figures 8 and 12) over the surface area examined. The average methane flow was evaluated at 11 Nml/min/m^2, giving a volume of CH_4 released of about 160 Nm^3 per day and per hectare of landfill area.

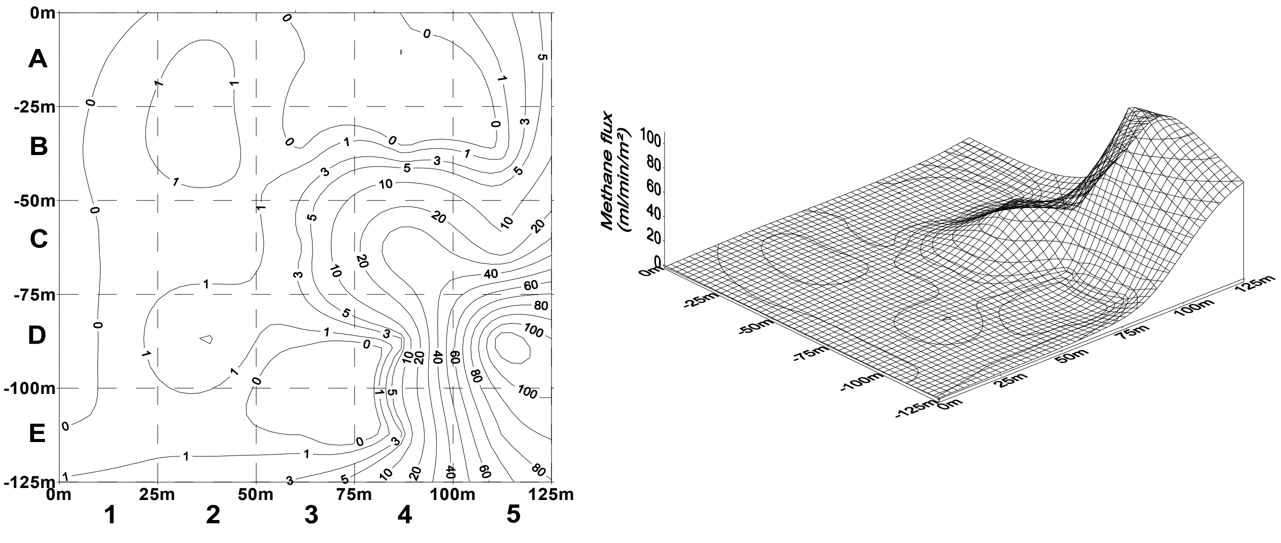

Figure 12. Mapping of methane emission obtained by kriging

This initial test can be seen as completely positive. But research is still needed in order to define the criteria of selection and the application areas of the different statistical methods as well as the practical means of implementing them.

9. CONCLUSIONS

One of the approaches used to measure gas surface flow often quoted in the relevant literature is the dynamic flux chamber. The principles involved were tested on a test bench in a first stage.

Tests showed that the **measuring equipment affected significantly the emission of biogas to the free air**. Consequently, the biogas flow rate measured on exit from the chamber was less than the value that might have been emitted from the surface area covered if there had been no chamber. **The ratio between the actual unaffected emission flow rate and the measured value can in certain cases be quite high (3 or even 4).**

In order to define the corrective factors required to compensate for the effect of the measuring on the measured flow, several simulations were effected on a test bench designed to be able to adjust and control the biogas flow. This validation of the method in the laboratory was required in order to define the analytical model whereby it would be possible to calculate the quantity emitted by the covered surface area once known the flow rate of biogas released from the chamber.

The pertinence of the measuring method concept as well as the analytical model issued from the laboratory test have been confirmed by a number of other tests conducted under actual conditions of methane emissions from a MSW landfill. This **experiments carried out *in situ* also confirmed the extremely high spatial heterogeneity of methane emission (ratio 1 to 10^4)**.

The work carried out has therefore produced a tried and proven method of measuring local flow densities of surface methane emissions. The method could in principle be applied in order to measure emissions of other gases produced from the surface, whatever the nature of the ground and the characteristics of the soil.

The studies carried out have also shown the possibility of determining the overall flow from a given site on the basis of local data, using a geostatistic method. That said, a more accurate methodology in respect of this approach remains to be defined.

The foregoing considerations do indicate the main lines of the work to be done in order to establish finally a reliable method of quantification appropriate to the nature of the phenomenon which is as complex as the gaseous emission rates from the areas considered are low.

10. ACKNOWLEDGEMENTS

The design and development of a method for measuring biogas emissions are the result of work performed by a whole team of INERIS engineers and technicians. We owe our thanks to the persons who have actively contributed to this study, in particular R. Geveart, J. Havard, M. Hugonie, A. Jodart and P. Jouglet.

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