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Infrared monitoring system for urban solid waste landfills: experimental activities for biogas outflow modelling

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Abstract

The present work concerns preliminary testing activities for the application of a ground based infrared system with spectral sensitivity in the 8-12 μm band to the detection of environmental risk conditions due to anomalous outflows of biogas and leakage in urban solid waste landfills. Calibrated surface temperature maps which outline anomalous areas affected by biogas release in the atmosphere were used for biogas outflow estimations through a thermal balance modeling. An experimental approach for thermal data calibration and model validation was followed as well.

1. Introduction

The anaerobic digestion of organic matter within an urban solid waste landfill produces biogas and water vapor which flow up to the surface through stored materials transporting the heat developed during waste fermentation. For this process, thermal anomalies at the surface are produced relating to the energetic waste yield and also to the permeability and thermal conductivity differences on material cover characteristics. Developments in infrared remote sensing techniques make rise the possibility of energetic, risk and management evaluations on the basis of surface temperature estimations [1]. The present work aims at the development of a remote sensing method in the thermal infrared region of the electromagnetic spectrum for risk monitoring through a quantitative analysis of biogas outflow distribution. The experiment was carried out in 1993 at the waste tip site of Literno (Isle of Elba, Italy) within the framework of the EC-MedSPA Project [2].

2. Biogas model

For the modeling of biogas outflow an energetic balance between generated heat by waste hotbed digestion and dissipated heat in the atmosphere was assumed. This balance is based on the following hypothesis:

a) all the heat is given to ground surface by condensation, whereas the fraction given to air is negligible
b) the used thermal image must be acquired when sun heat contribution can be considered negligible (i.e. sunset-predawn conditions)
c) thermal equilibrium conditions are supposed, therefore thermal anomalies are defined as those areas where surface temperature is higher than the air's, due to heat generated from anaerobic digestion which produces methane
d) biogas is generated by a homogeneous single layer of waste uniformly affected by digestion processes; therefore heat dissipation phenomena within each layer are neglected assuming a constant value of the temperature along the path to the surface

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e) the wind speed must be lower than 6.1 m/sec.

On these bases, the generated heat (Q_g) in the time unit is proportional to biogas outflow (Q_M) (Kg/h) and to the difference (ΔT) between air and biogas digestion temperatures (T_a-T_i) (°K) through a constant defined by the biogas specific heat (C_m) (Kcal/Kg °K):

$$\frac{\Delta Q_g}{\Delta t} = Q_M C_m \Delta T \tag{1}$$

whereas the dissipated heat (Q_d) in the time unit depends on both a radiation and a convection heat term:

$$\frac{\Delta Q_d}{\Delta t} = \sigma e (T^4 - T_a^4) A + h_c \Delta T_s \tag{2}$$

where σ is the Stefan-Boltzmann constant (4.88 10^{-8} Kcal/h m^2 °K^4); e is the surface hemispherical emissivity over all the electromagnetic spectrum; T (°K) is the anomalous surface temperature for the area A (m^2); ΔT_s is the difference between T and T_a; V is the wind speed (m/s); and h_c is the coefficient of thermal convection exchange (Kcal/h m^2 °K):

$$h_c = (5 + V \frac{3600}{1100}) \tag{3}$$

Consequently thermal anomalies at the landfill surface are related to the biogas discharge Q_V (m^3/h) as follows:

$$Q_V = \frac{\sigma e (T^4 - T_a^4) + (5 + V \frac{3600}{1100}) \Delta T_s}{D_m C_m \Delta T} A \tag{4}$$

where D_m is the biogas density (Kg/m^3);

A sensitivity analysis was carried out in order to test the influence, in terms of absolute and relative error, of input parameters accuracy on the model's biogas discharge calculations [2]. In *table 1* parameters values used for the sensitivity analysis are shown; whereas absolute and relative errors on biogas discharge as a consequence of errors on the estimation of input parameters are shown in *table 2*.

Table1: *Input parameter values used for the sensitivity analysis.*

INPUT PARAMETER	VALUE
Emissivity	0.98
Surface temperature	20°K
Air temperature	15°K
Digestion temperature	35°K
Wind speed	0.5 m/s

Table **2:** *Sensitivity analysis results.*

ABSOLUTE ERROR ON INPUT PARAMETER	ABSOLUTE ERROR ON BIOGAS DISCHARGE	RELATIVE ERROR ON BIOGAS DISCHARGE %
Δe=0.1	0.004 Kg/h Apixel	4.20
ΔT=1°K	0.018 "	20.33
ΔTi=1°K	0.005 "	5.50
ΔTa=1°K	0.014 "	15.55
Δv=1m/sec	0.026 "	28.89

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In *figure 1* an example of the relationship between the biogas discharge (Kg/h per pixel area unit) estimated with the model and the landfill surface temperature, derived from infrared thermography, is shown for the given input values.

In order to process thermal images and biogas outflow map generation during waste site surveys the biogas model was inserted in an MS-DOS modular software tool which is made up by different programs implemented by using Fortran and C languages:

a) the generation of the calibration Look Up Table between DN and brightness temperature for the specific sensor on the basis of the observed minimum and maximum values;
b) the visualization of the calibrated thermal image;
c) the estimation of biogas discharge to the pixel unit area on the basis of surface temperature maps on those areas where thermal anomalies ($T>T_a$) occur;
d) the visualization of the biogas discharge map of the whole site;
e) the visualization of discharge values for selected areas of variable size (n.of squared pixels) on the biogas discharge map;
f) the output of a "biogas.log" file where, besides input parameters, ancillary parameters are also listed (density and specific heat, of water vapor, dry biogas and humid biogas)

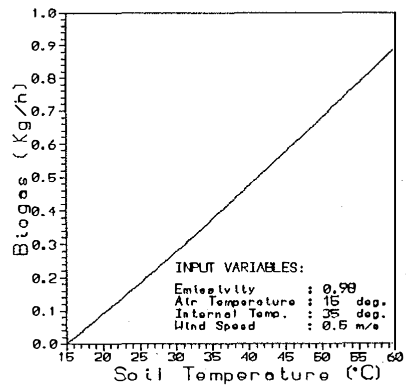

Fig.1: *Biogas discharge estimated with model as function of landfill surface temperature, derived from infrared thermography*

3. Methods

The experiment was carried out from an elevated overall view position, about 500m outside the landfill plant area. Infrared images of landfill steps were acquired from that location during the descending thermal diurnal cycle when the influence of solar charge was negligible. In *figure 2* an example of a digital mosaic of high spatial resolution (25 cm) infrared images of the Literno landfill is shown. In this case the gray levels in the picture are linearly stretched to enhance thermal contrasts between different waste sites.

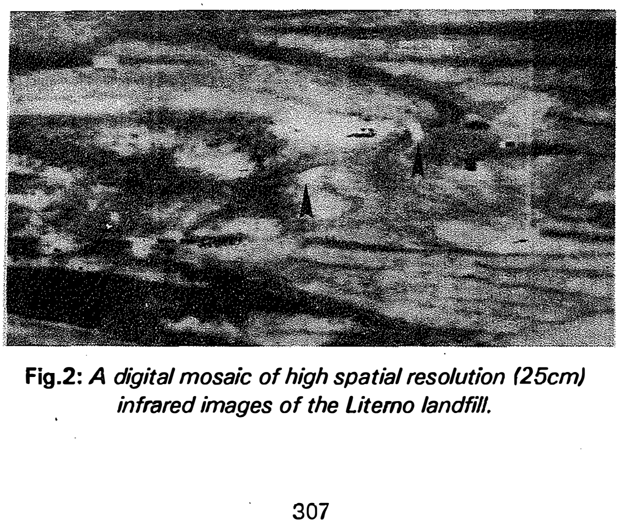

Fig.2: *A digital mosaic of high spatial resolution (25cm) infrared images of the Literno landfill.*

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The "portable landfill monitoring system" was designed as a system made up of an infrared INFRAMETRIX IM600 camera (8-12 μm) which acquires thermal data supplying a standard video signal to a VHS videotape recorder and to a video signal data acquisition card (Matrox PIP). A portable 386 PC was used for data filing, image processing and real time biogas outflow map computing.

The thermal camera is a HgCdTe sensor with 2mrad IFOV and 0.1°K temperature resolution, an internal thermal reference and a processor both allow radiance and brightness temperature measurements through a calibration LUT.

In order to check the camera calibration, two aluminum black-smoked colored plates at different temperature conditions were used; whereas an aluminum plate with two sections at different emissivity values (a black colored one and a Lambertian rough one) was also used to estimate the background radiation [3].

The detection of thermal anomalies was enhanced by means of a multilook approach averaging four images of the same observed scene and resulting in an improvement of about 2-3 dB of the S/N ratio.

A set of ancillary measurements was also collected simultaneously with infrared images to allow data calibration procedures and boundary conditions estimation for the biogas outflow model validation. The sky cover conditions were taken into account for valuations of the background contributions, as well as minimum and maximum temperatures over the observed landfill area which were noted down for image calibration. The air temperature and the wind speed were monitored to identify thermal anomalous conditions ($T > Ta$) and save model validation tests when the wind speed was higher than limit conditions (6m/s). Moreover, biogas was sampled at the top of the deepest drain-pipe to provide the model chemical composition data for energy calculations and finally the biogas temperature that was assumed as the digestion temperature, was monitored by means of a PT100 placed into the surface basement of the same drain-pipe.

4. Experimental results

The validation of the biogas outflow model was performed in relation to the deepest drain-pipe area where the biogas outflow was relatively higher than the other ones and the measurement of biogas discharge was easily made possible by means of a "shaded anemometer" (see arrowhead hot spots in *figure 2*). The one meter diameter drain-pipe made by stone filled wire-netting was dressed with a nylon sheet as a manifold for biogas collecting and discharge measurements. For that reason an emissivity value of 0.8 was assumed, which is unlike the average 0.94 value for landfill areas covered by clay-loam terrain [4].

A model simulation was run for input parameters shown in *table 3* in which the results of the model tests on two infrared images are shown as well.

Table 3: *Measured parameters and results of the model validation tests.*

Time	CH_4 (%)	CO_2 (%)	V (m/s)	Ta (°K)	Ti (°K)	e	Measured Qv (m^3/h)	Estimated Qv (m^3/h)	Rel. error (%)
25/11/93 5.20pm	10.0	6.5	0.0	11.0	35	0.8 nylon	17.0	15.48	-8.9
25/11/93 7.05pm	10.0	6.5	0.4	7.5	35	0.8 nylon	16.6	16.05	-3.3

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5. Comments and conclusions

Results of the above described experiment positively lead to the waste-disposal sites monitoring by means of ground based and airborne systems operating in the thermal infrared bands. Good reasons for this refer to capability of temperature anomalies detection on the processed thermal images, and also to the performance of biogas outflow model through thermal balance calculations.

Besides positive perspectives for the development and the application of the system, crucial aspects regarding the calibration of the infrared images and the modeled processes have to be improved for future experiments.

In order to input a corrected surface temperature map into the biogas model, an emissivity map, which takes into some consideration observation angle and surface wetness, as well as the knowledge of background contribution to the measured radiance, are necessary. From theoretical evaluations [2],[3], a 10% of uncertainty on surface wetness and not evaluating the local observation angle when it is lower than 60°, will produce a 4% error on emissivity estimation and about a 2°K of maximum error on surface temperature estimation which lead to a 40% maximum relative error on biogas discharge estimation (see *table 2*). The same error on biogas discharge will be introduced by the background contribution in night time clear sky conditions which has about +2°K effect on surface temperature estimation [2].

Moreover, future releases of biogas model will consider also the heat fraction which is given to the atmosphere with a foreseen reduction effect on biogas discharge and an increase in error on the estimated value; therefore, the validation of the model will be concluded when the simulation results on waste sites of different age and energetic yield are evaluated.

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