

HEAT RECOVERY IN COMPOST PILES FOR BUILDING APPLICATIONS

by

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This work proposes an estimation of the possible heat recovery of self-heating compost piles for building applications. The energy released during the aerobic composting of lignin and cellulose-based materials is computed by solving an inverse problem. The method consists first in an experimental phase with measurement of the temperature within the heap, then a numerical procedure allows for the inverse identification of the heat production due to the chemical reaction of composting. The simulation results show a good accordance with the experiments for the chosen source-term model. Comparing the results to the theoretical values for the energy released by aerobic composting provides an estimate for the efficiency of the reaction. The reached temperatures and recovered energy fit with the order of magnitude of building needs.

Key words: *heat recovery, aerobic composting, inverse identification, lignin*

Introduction

In numerous countries, the recent evolution of the building construction and retrofitting regulations sets a trend towards more local, distributed energy production system vs. centralized ones, as well as renewable energy targets [1]. This inclination could be part of a solution in order to reduce the 30% contribution of the European housing sector to GHG emissions [2]. In the French context, the building sector consumption is responsible for 43% of the GHG [3] and the new building regulation orientates the market towards a more sober residential sector, with overall energy consumptions ranging between 0-50 kWh/m² per year [4].

In the frame of this work, we will not consider anaerobic composting in bioreactors leading to CH₄ production. This topic is studied for example in [5, 6], whereas aerobic composting for heat recovery purposes is less often examined. Aerobic composting is usually done at larger scales in cooperation with local communities providing degradable waste, heat recovery being possible such as in [7, 8]. Aerobic composting hence provides an alternative for decentralized, biosourced energy. The temperature range of 25 to 80 °C fits well for building applications such as air heating, floor heating or domestic hot water service. This technique was however already explored: in the mid 1970's [9], the self-made scientist called Jean Pain described a method for retrieving thermal energy from a heap of shredded plant waste, mainly

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branches. According to his experience, he managed to heat up his house and produce hot water service up to 57 °C for two years by composting roughly 100 m³ of shredded wood. In order to validate this concept and possibly to design efficient compost-based energy recovery systems for building applications, there is a need for a consistent model describing heat production in such heaps.

Self-heating in compost piles is driven or strongly influenced by several potentials: chemical reaction, bacteria population [10], oxygen supply, heat transfer, and moisture content [11]. The numerous and complex interactions between the phenomena at hand in the reaction lead to two types of approaches of self-heating compost heaps modeling.

The first type is a full-scale model including heat, mass, and oxygen transfer within the pile such as [12]. However, such biological and thermochemical phenomena leading to an increase of temperature is a multi-scale heat flow and component coupling problem, taking place in a changing and deformable porous media. The available shredded wood coming in our case from the local landfill site is also very heterogeneous in terms of composition or heat and mass transfer coefficients, making it difficult to describe faithfully reality with such models. Based on this observation, we considered a blunt approach allowing identifying the amount of energy released by shredded wood piles, as well as the source terms of the reaction for practical energy calculations, hence characterizing the heterogeneous mixture as a homogeneous pile.

The phenomenon we consider consists in two phases. At first an exothermic chemical reaction (lignin and cellulose degradation) produces temperatures varying from 70 to 80 °C [10] depending on the species of plant used and the set-up insulation. A lower temperature bacterial reaction ranging from 25 to 40 °C comes after the temperature peak. The experimental set-up used allowed to study the aerobic reaction, *i. e.* without CH₄ production. The temperature increase is simulated by an exothermic chemical reaction.

The literature review provides elaborate numerical or analytical models of self-heating compost heaps such as [13, 14]. However, to the best of our knowledge, only little amount of authors confront their results with the experiment. Conversely, experimental communications about compost piles do not propose numerical models for their set-up [15], hence the need for more papers unifying both approaches such as in [12].

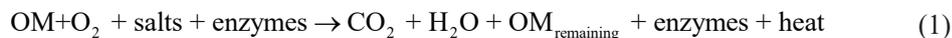
In the present work we will first explore the theoretical background of aerobic composting as well as the experimental set-up and procedure. The numerical model of the problem and the parametric identification routine are then detailed and finally we confront numerical results with the experiments with a focus on building usage.

Basics of aerobic composting

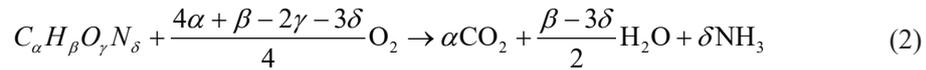
In presence of oxygen, the decomposition of organic matter occurs in three phases.

- The mesophile phase: the organic matter is metabolized thanks to enzymes by mesophile bacteria at middle range temperatures (about 30 °C). This phase lasts between 5 and 10 days and generates an important temperature increase within the first 24 hours.
- The thermophile phase: in this phase the thermophile bacteria dominate the reaction. The temperature in the heap may reach 70 °C.
- The maturation phase: the remaining organic matter is degraded into carbonated matter (*i. e.* mineralization). One observes the formation of fulvic and humic acid.

The actual product, responsible for the degradation of matter are the enzymes of bacteria and/or fungi. The three aforementioned phases translate into eq. (1), where OM stands for:



The presence of remaining OM means the reaction is not total. Yet considering the reaction as total, the previous equation turns into the general formulation:



From eq. (1), one could think oxygen is the only limiting reagent. Nevertheless, it is to be noted that bacteria populations need a combination of O_2 , water and appropriate temperature for an optimum development. The fungi responsible for wood decay and especially lignin degradation [16] also need adequate oxygen and moisture conditions.

Wood is simplified as a mixture of cellulose, hemicellulose ($C_6H_{10}O_5$) and lignin [17]. The first two components are well known and degraded by bacteria.

Lignin has a more complex structure and is thus highly recalcitrant to degradation by most organisms. Indeed, lignin is a non-carbohydrate aromatic heteropolymer of three different units derived from p-coumaryl alcohol, coniferyl alcohol, and sinapyl alcohol. The abundance of these monomers and their linkages vary according to the plant species and plant tissue [18], hence the difficulty to find a general formulation for the degradation energy of wood. Fungi (especially white-rot fungi) are the most effective for degradation of lignin, due to production of ligninolytic extracellular oxidative enzymes [19, 20]. Interestingly, different soil bacteria species contribute to the degradation of lignin, by expressing similar enzymes to those found in fungi [20].

By simplifying its components as being merely a mixture of cellulose, hemicellulose, and lignin (using $C_9H_{10}O_2$ as chemical composition [17]), an order of magnitude of the energy contained in wood can be calculated. The standard enthalpy of reaction gives the ideal chemical energy content, which is plotted vs. the fraction of lignin on fig. 1. For a mixture of 70% cellulose and hemicellulose and 30% lignin [17], eq. (2) yields $E_{ideal} = 7.13$ kWh/kg. The actual energy amount that can be withdrawn from wood degradation is however smaller: the reaction is not complete, thus a certain amount of organic matter does not react, leading to maximum energy content E_{max} . The edge effects, the heat losses to the ambience by transmission and aeration of the heap are also to be accounted for, whence the real energy amount E_{real} , as depicted on fig. 1.

An optimal heat recovery system would have to reduce the aforementioned irreversibility's by homogeneous degradation of matter and lessened heat losses as well as edge effects and controlled ventilation.

Experimental procedure

The aim of the experiments is to record the reached operating temperatures at a given point of the heap and the duration of the reaction. In order to optimize the process and to predict heat production for different geometries, the thermophysical properties of the matter used were

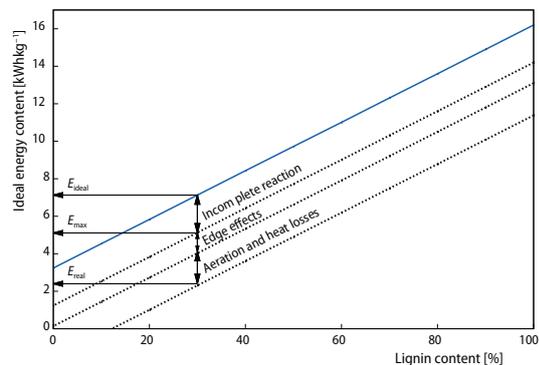


Figure 1. Ideal energy content of cellulose, hemicellulose, and lignin mixtures depending on the lignin content

measured, so as to be able to compare the results with the simulation and fit the chemical reaction's parameters as described in section *Numerical model and inverse identification*.

Table 1. Description of the set-ups

Exp.	Material	Dimensions [cm ³]	Aeration pipes	Insulation material
1	Leaves	89 × 56 × 138	6	5 cm polystyrene ($\lambda = 0.04$ [Wm ⁻¹ K ⁻¹])
2	Shredded			
3	wood			

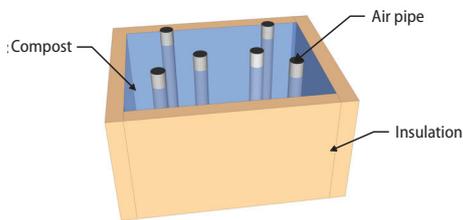


Figure 2. Scheme of the set-ups

The characteristics of the experiments are described in tab. 1. The insulated box was mainly filled with fallen leaves for experience 1, whereas experience 3 and 4 were lead with a majority of shredded wood.

In order be able to simulate the temperature evolution in the compost heap, the conductivity, density, and thermal capacity were measured. These features can depend on the progress of the biochemical reactions, however, we considered they remain constant in the frame of this work. The measured properties are summed up in tab. 2.

Table 2. Thermophysical properties of the experiments

Exp.	Conductivity [Wm ⁻¹ K ⁻¹]	Density [kgm ⁻³]	Thermal capacity [Jkg ⁻¹ K ⁻¹]
1	0.3	800	3300
2	0.097	318	3249
3	0.131	325	3250

made of green waste and our experience No. 1 are qualitatively similar and the comparison between these two types of matter exhibits a different magnitude and duration. However, we cab observe an equivalent dynamic behavior and about 10 K temperature increase. Noticeably, the insulation of our set-up allowed for a slightly higher temperature increase than [15]. For heat recovery prediction and improvement, there is a need to identify the energy content and driving potentials of such reactions. The modeling attempt shall allow to access these governing parameters for low temperature appliances.

Numerical model and inverse identification

The chosen thermochemical model is presented along with the corresponding set of controlling parameters and boundary conditions. The equivalent chemical driving potentials are to be identified by the means of an inverse method.

We chose to represent the exothermic degradation of lignin and cellulose by a set of two partial differential equations. This system comprehends on one hand the energy conser-

A plane-parallel, insulated box is filled with an initial volume of shredded wood and leaves, tab. 1, from a mixture of different tree species and instrumented with temperature sensors at central positions in the heap so as to diminish the edge effects. The box containing the mixture is thermally insulated by 5 cm of polystyrene. We chose to supply air to the reaction by inserting drilled PVC pipes within the heap as depicted in fig. 2. The volume of air supplied is induced by chimney effect and remains globally weak due to the material's flow permeability. The Peclet number in the PVC pipes is also very low and we will hence neglect this parameter in the numerical model for the sake of simplicity.

The obtained temperature evolution is given on fig. 3, where we can see the increase in temperature due to the source term up to 200 hours and the decrease afterwards.

The temperature profiles of both Hasan *et al.* [15] set-up No. 1, fig. 4,

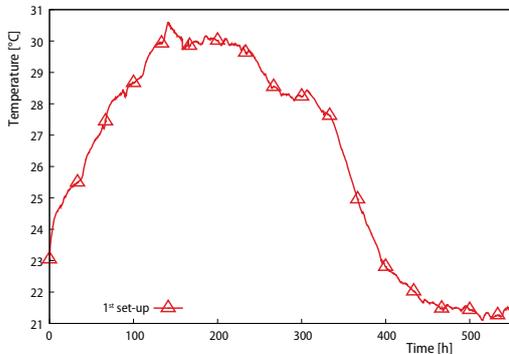


Figure 3. Experience 1 at point (15, 35, 37) [cm]

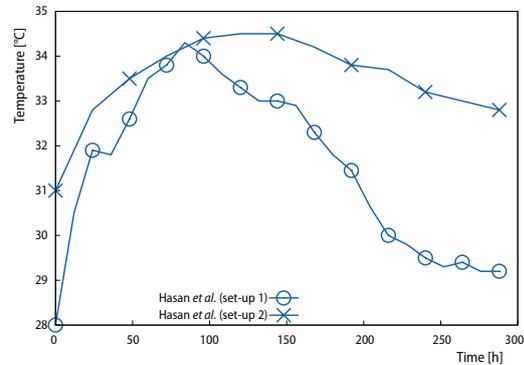


Figure 4. Hasan *et al.* [15] results

vation equation with a volumetric source term, S , eq. (3), and on the other hand the change of lignin and cellulose content over time. This content corresponds to a concentration dependency as well as a temperature dependent phenomenon, namely Arrhenius law with the energy of activation E_a , eq. (4). This equation stands for the sensitivity of bacteria and fungi development to temperature. Amongst numerous linear and non-linear concentration models explored, that model happened to be the most complying with our experiments.

Our two equations model, eqs. (3) and (4), is a simplification of the global coupling and the different physical interactions, such as gas interdiffusion in the fluid phase (O_2 , CO_2 , water vapor) and diffusion of water and water vapor in the solid phase (sorption and especially temperature driven desorption of the hygroscopic water contained in shredded wood). Such assumptions reduce the focus mainly on the active product concentration which is a necessary condition of the phenomenon, hence including all the linearized couplings within the k coefficient. The set of equation is as follows:

$$\rho c_p \frac{\partial T}{\partial t} = \lambda \Delta T + S \quad (3)$$

$$\frac{dC}{dt} = -k C e^{-\frac{E_a}{RT}} \quad (4)$$

The coupling between heat diffusion and chemical reaction occurs through the energy source term, S , given by:

$$S = H \frac{dC}{dt} \quad (5)$$

For the sake of simplicity, as the quantity H of energy released per mole is not known and due to the complexity of the chemical formulation, we introduce a new concentration variable such as $c = HC$ and hence identify directly the energy content of the reagent in [Jm^{-3}] (when used for building comparisons, it will be noted E in [$kWhkg^{-1}$] or [$kWhm^{-3}$]). The reacting matter is hence merely seen as an energy content and eqs. (4) and (5) turn into:

$$\frac{dc}{dt} = -kce^{-\frac{E_a}{RT}} \quad (6)$$

$$S = \frac{dc}{dt} \quad (7)$$

The models of boundary and initial conditions are given:

$$c(x, y, z, t = 0) = c_0 \quad (8)$$

$$T(x, y, z, t = 0) = T_0 \quad (9)$$

$$\vec{\phi} \cdot \vec{n} = h[T_w - T_{\text{amb}}(t)] \quad (10)$$

In eq. (10), h is the global heat transfer coefficient including the insulation's thermal resistance, as well as the external air heat transfer coefficient and $\vec{\phi}$ is the heat flux. The flux boundary condition then depends on the recorded ambient temperatures, thus allowing for a more precise determination of the time dependent heat losses. The initial temperature, T_0 , is known whereas the initial concentration, c_0 , is unknown, as it depends on the variety of sample used, hence the utility of the inverse approach to identify the c_0 value as well as the partial differential equations parameters k and E_a .

The numerical model is 3-D with a regular meshing. The simulation results were benchmarked vs. an analytical solution and a sensitivity study was led in order to obtain a consistent approximation of the time and space discretization.

The aim of the inverse identification is to find the best set of parameters allowing for the numerical model to properly match the measured temperatures at a given position (x_s, y_s, z_s) within the heap for all recorded data over time. Fitting the parameters of the partial differential system of eqs. (3) and (6) was carried out by an iterative procedure using *trust-region* minimization algorithm [21] coupled to our finite difference calculation routine, fig. 5.

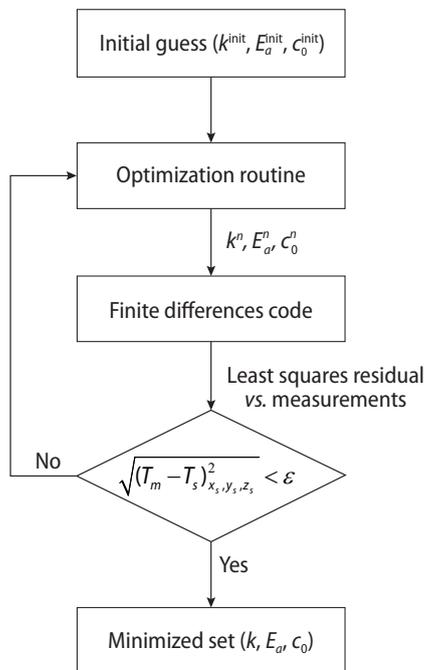


Figure 5. Principle of the inverse identification

Results and discussion

Following section presents the comparison between experimental data and simulation results. The leaves-based tests will be presented first and then the shredded wood degradation tests, as well as the fitted parameters k , E_a , c_0 for each experiment. Eventually the results will be discussed.

Leaves composting – Experience No. 1

The evolution of temperature within the aerated heap of leaves was measured and the parameters (k , E_a , c_0) were fitted in order to minimize the discrepancy between numerical and experimental curves, as presented in fig. 6. The simulation shows a proper approximation of reality over the measured period. For experience 2, the dynamics and absolute values are captured correctly. At the end of the test period, the quantity of leaves filling the reactor was qualitatively much dryer, leading to 10% difference between the initial volume of leaves and the final one of the partly composted leaves.

From our experience and from skilled in the art person, leaves are subject to flocking together under the effect of humidity and own weight, which leads to volumetric variation during the process of degradation as well as the formation of hardly air-permeable *strata* inhibiting the reaction by limiting the oxygen supply. Experiments 2 and 3 will allow the investigation of shredded plants with a higher porosity and a lesser dependency to shrinking during the reaction.

Shredded wood – Experiences No. 2 and 3

Experience No. 2 was made of freshly shredded wood of average size 3 cm. It shows a noticeably higher temperature peak than experience 1, as presented in fig. 7. The discrepancy between simulation and measurements can possibly be explained by the uneven diffusion of oxygen and water, which insufficiency limit the reaction of aerobic composting. Indeed, after the end of the experiment, we noticed that only the lower 15 cm of the heap had properly broken down into compost, the upper part of the heap being conveniently aerated but very dry, which means the contained energy amount is to be higher, as discussed at the end of this section.

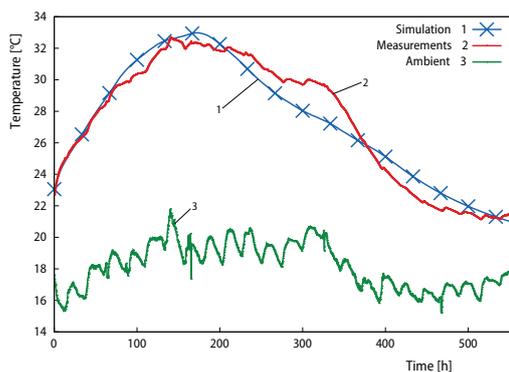


Figure 6. Experiment and numerical results, temperature vs. time at point 43, 34, 50 cm for exp. No. 1

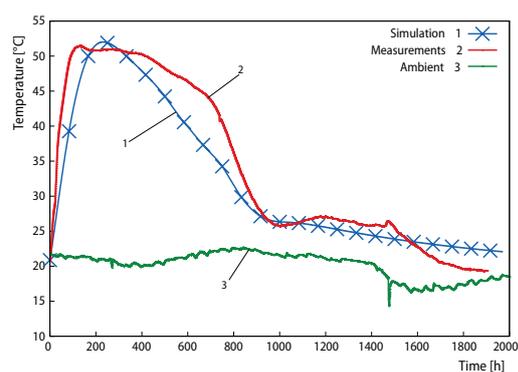


Figure 7. Experiment and numerical results, temperature vs. time at point 43, 34, 50 cm for exp. No. 2

Experience No. 3, also composed of freshly shredded wood, shows a similar shape and the model show a correct accordance with the measurements, fig. 8. Both experiences 2 and 3 peak values are similar, however the reaction's duration is much shorter: after 300 hours (less than 2 weeks), the heat production is insignificant, whereas for exp. 2 it takes about 900 hours (6 weeks) for the reaction decrease to temperatures close to the ambience.

Analysis of the experiments

Interestingly, the behaviors of all three tests have different shapes, as presented on fig. 9 where the previous three measured temperatures are displayed with the same time and temperature scales. The lower temperatures stand for leaves-based test (experiment 1), the higher ones for shredded wood (experiences 2 and 3).

Experiments 2 and 3 have similar amplitude, however, their durations show a ratio of approximately five. It may thus prove to be interesting for low energy buildings needs, based on the reached temperature level which fits well with the current low temperature central heating systems, e. g. experiment 2 on fig. 9 shows a potentially useful temperature plateau around 50 °C for about a month. At the contrary, it may fail to provide such conditions, see experiment

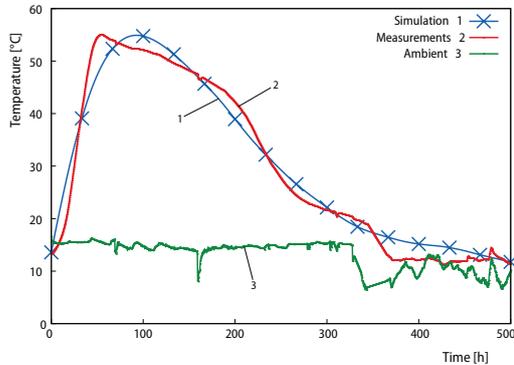


Figure 8. Experiment and numerical results, temperature vs. time at point 43, 34, 50 cm for exp. No. 3

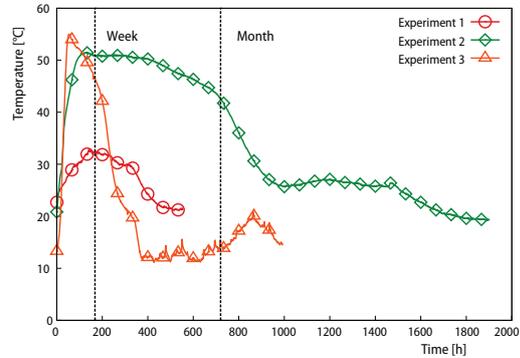


Figure 9. Comparison of all experiments – temperature in the three piles vs. time

3 on fig. 9. The uneven distribution of bacteria, fungi, temperature, moisture, and oxygen in the medium due to inhomogeneity's are most likely responsible for such differences.

Results of the parametric identification

The results obtained with the set-up used in the present study are encouraging, however, they exhibit the difficulty of predicting the heat released due to the origin of the plants used. Their species is not known as they come from the available matter from the local waste management facility.

The energy released by the heap during the reaction, E_0 , is computed thanks to our inverse identification procedure. The results of the minimization procedure are summarized in tab. 3. We define the reaction effectiveness, E , as the ratio between the released identified energy and the ideal chemical binding energy $E_{ideal} = 7.13$ kWh/kg as detailed in the section *Basics of aerobic composting*:

Table 3. Numerical results for k , E_a , c_0 , E_r , and ε

Exp.	k [s]	E_a [kJmol ⁻¹]	c_0 [Jm ⁻³]	E_r [kWhm ⁻³]	E [%]
1	$1.301 \cdot 10^{-1}$	30.5	$2.38 \cdot 10^8$	66.2	2.2
2	$1.649 \cdot 10^{-3}$	21.9	$2.89 \cdot 10^8$	80.5	6.6
3	$1.702 \cdot 10^{-2}$	21.5	$7.94 \cdot 10^7$	22.1	3.8

as detailed in the section *Basics of aerobic composting*:

$$\varepsilon = \frac{E_0}{E_{ideal}} \quad (11)$$

As one can see, the effectiveness results are very low compared to the ideal case. This can be explained by different factors,

- the inhomogeneity's of the medium result in unequal oxygen and CO₂ distributions, leading to the inhibition of the reaction [22],
- the aforementioned inhomogeneity's provokes unequal temperature distribution within the heap, which affects the temperature dependent reaction [23],
- moisture content is a necessary condition for bacteria and fungi to degrade OM but it is included in the model, and
- the reaction is not complete, hence the higher discrepancy to E_{ideal} , fig. 1.

The importance of these parameters is confirmed by the low quality of the compost. At the end of the tests, most of the shreds had not actually broken down into compost. Comparing with the results of [24] that range from 4.08-5.54 kWh/kg for and aerated, stirred mixture of biowaste and straw, one can reasonably improve the heat output by an order of magnitude. Sup-

posing such a domestic system could reach 4 kWh/kg energy recovery, the quantity of shredded matter for a 100 m² house with *Passivhaus* standard consuming 15 kWh/m²y heating would be 375 kg, which represents a volume of ~1 m³.

Conclusion and perspectives

In this study, the potential of aerated green waste piles for low temperature applications and building use through chemical degradation was explored. An explicit 3-D finite differences model was developed in order to simulate the temperature field within degrading matter and the order of magnitude of the energy released by inverse identification.

A simplified model revealed to be complying with reality in the domain of temperature where the experiments were led, between 10 and 55 °C. The discrepancy between the model and the experiment may be explained by the heterogeneous distribution of reagent (oxygen, moisture) and the variability of some parameters, taken as constant in the model (density, conductivity, heat capacity). Assuming a negligible Peclet number in the aeration tubes also leads to imprecision in heat losses and reduces the amount of available energy as presented on fig. 1.

The effectiveness numbers defined as per paragraph *Results of the parametric identification* are very low for our static set-up compared to the ideal amount of energy contained in green waste. The reaction duration is also very variable, even when similar material used, making it difficult to use the system as it is. Efforts need to be put in improving the reaction, such as mechanically aerating the heap [25, 26] and providing sufficient moisture conditions. Insuring a better thermal insulation would also improve the effectiveness of the reaction, as well as implementing a heat exchanger on the induced air. This will be the objective of some further experiment at our test facility.

The results are however promising for a locally sourced energy fueling housing demand. The tests allowed for the assessment of a compatible range of temperatures and duration for this sector. The independence of this energy source with the season is also to be taken into account. It is obvious from the results and the comparison with [24] that improving the process would permit a much higher energy recovery. It could indeed provide a complementary source to solar energy or insure preheating. The identification procedure and the model developed will allow for the prediction of yearly energy production of a novel, innovative integrated system such as [27].

Nomenclature

C – chemical concentration, [mol m⁻³]
 c – energy content, [Jm⁻³]
 c_p – thermal capacity per unit mass of compost, [Jkg⁻¹K⁻¹]
 E – energy content, [kWhm⁻³]
 E_a – Arrhenius constant, [Jmol⁻¹]
 H – exothermicity of the reaction, [Jmol⁻¹]
 h – global heat transfer coefficient, [Wm⁻²K⁻¹]
 k – reaction constant, [s⁻¹]
 R – constant of ideal gases, [Jmol⁻¹K⁻¹]
 T – temperature, [°C]
 t – time, [s]
 x, y, z – spatial co-ordinates, [m]

Greek symbols

α, β – integer coefficients, [-]
 λ – thermal conductivity of compost [Wm⁻¹K⁻¹]
 ρ – density of compost, [kgm⁻³]

Subscripts

0 – initial value
 amb – ambient
 m – measured
 r – released
 s – simulated
 w – wall boundary

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