MODELLING AND ELEMENTS OF VALIDATION OF SOLAR DRYING: APPLICATION TO ACTIVATED SLUDGE DRYING OF WASTE WATER

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This paper presents a simulation code for the solar drying of sludge. This code is using a model of the drying kinetics of wastewater sludge, and takes into account water transport in the product during drying.
An application of the FAST method for the parametric sensitivity test of this code has been used in order to highlight influencial parameters on the solar collector model. Finally, it is shown that outputs of the model, could be approached by a regression polynomial called "metamodel" created from sensitivity analysis. Sensitivity analysis becomes an alternative in order to model a system, working under various weather conditions.

Keywords: solar energy, simulation, sensitivity analysis, mass flux, spectral analysis

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Publications: Modelling of drying activated sludge: effects of the sludge turn over on drying kinetics, International Conference on Advances in Mechanical Engineering and Mechanics, ICAMEM 06, December, 2006, Tunisia.
Theoretical and Experimental study of activated sludge drying of waste water, International Conference on Engineering for Waste Treatment, May, 2005, Albi, France.
Drying granular porous media: mixing effects of activated sludge on the kinetics of drying, International Communication of Heat and Mass Transfer, 2007 (under review).

Introduction

Since 1 July 2002 in Europe, the law No. 92-646 of 13th July 2002 has prohibited the disposal of sludge that contains less than 30 % dry matter in storage centers. Studies of methods of drying the sludge using a renewable energy are an attempt to solve this problem.
The present theoretical study focuses on modelling the solar drying. A practical application of solar drying is the activated sludge of waste water drying. The paper also focuses on modelling the drying kinetics of the sludge. The model takes into account water transport between the sludge and drying air during drying that would occur within a laboratory solar dryer operating at low temperatures.
Then we conducted a parametric sensitivity analysis, using the FAST (Fourier Amplitude Sensitivity Technique) method, on the elaborated model. The analysis is concerned with the sensitivity of the model in relation to functional parameters (e.g., meteorological parameters, flow rate, and temperature) and structural parameters (e.g., geometrical parameters, orientation of the collector, and thermo-physical features).
The new sensitivity testing technique outlined in this study identifies the most influential parameters.
This approach will demonstrate the influence of functional parameters such as the temperature, flow rate, and relative humidity of the drying air, parameters that can be perfectly controlled during the drying. This analysis will show that the influence of product size is less significant than the effects of these three parameters. In order to improve the model it is important to control these parameters or accurately measuring them. In this way, the gain of heat conveying air temperature at the output of the solar collector model could be represented by a polynomial of regression called "metamodel". This model is a combination of the most important parameters.
In the first part of this article, the dynamic model will be presented, and then the sensitivity analysis will be applied to improve the modelling.

Theoretical analysis

Modelling of the solar drying system

Modelling of the drying system

The solar drying is composed of a drying room coupled with two solar collectors. This kind of dryer belongs to the family of the active driers [1]. The solar collectors are placed upstream drying room and set aside to heat or to preheat air before make one's entrance into the drying room.

Functional and architectural description of the dryer

The dryer is a cupboard-shaped room, with the lower part containing drying air that is aspirated from ambient air by a centrifugal fan and heated by an electric balance system of heating. This hot air is blown upward and into contact with the product sample. The samples are spread in thin layers in the shape of small disks placed on one or more trays arranged vertically. Humid air is removed from the dryer via evacuation openings.

Fig. 1 is a schematic diagram of the dryer and shows how the product samples are situated within the drying room.

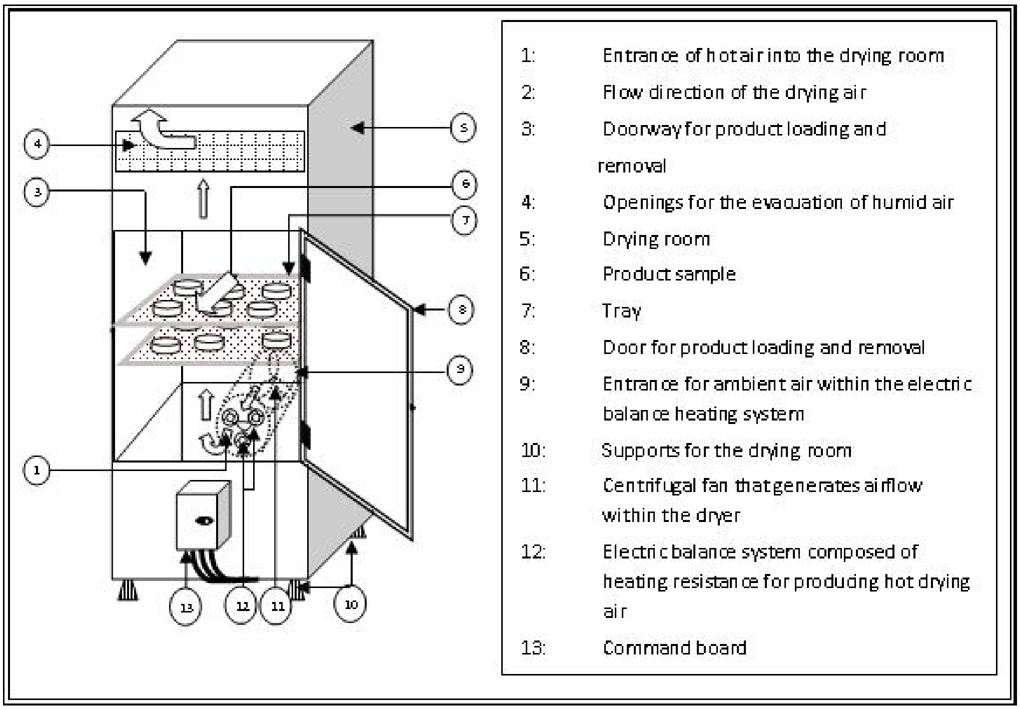


Fig. 1. *Schematic drawing of the studied drying system*

Simplifying hypotheses for dryer modelling

As simplifying hypothesis for modelling the drying room [1], the following transfers were neglected:

– heat exchange with the ceiling and the floor of the room;

– thermal exchange related to the condensation of humid air on the internal surfaces of the drying room;

– heat exchange with trays, heat exchange related to the thermal inertia of the drying air;

– heat and mass exchanges between samples.

In addition, it was assumed that samples are shaped like small disks, the solar flux density received by the four surfaces of the drying room is uniform, and that the sludge temperature on each tray is uniform. (diameter, thickness).

Equations of thermal balance

The drying room was subdivided such that each sub-area slice contains a tray. Thus, Fig. 2 describes the thermal exchange phenomena [2] taking place with the *i*-th representative slice of the drying room. On the basis of analogy between electric and thermal factors, an electric circuit equivalent to all the thermal exchanges occurring with this sub-area slice is shown on Fig. 3.

By applying Ohm's law to every node of the circuit, we derive a non-linear system of five partial derivative equations of the following shape:

$$C_k \frac{dT_k}{dt} = \sigma_k + \sum_{j=1}^{n} \left[\left(R_{kj} + H_{kj} + C_{kj} \right) \left(T_j - T_k \right) \right]. \quad (1)$$

The differential equation system is solved for each segment in the time domain using 4th order Runge-Kutta method.

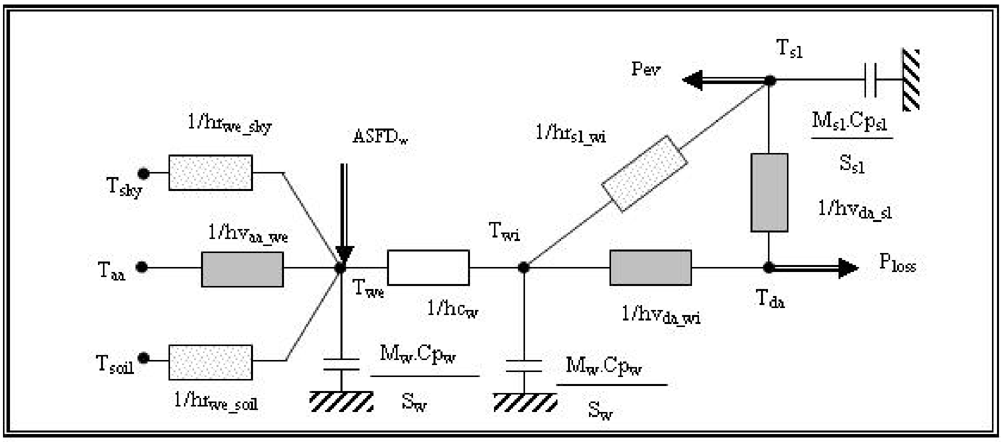


Fig. 2. *Schematic description of thermal exchange phenomena taking place at the i- th fictitious representative slice of the drying room*

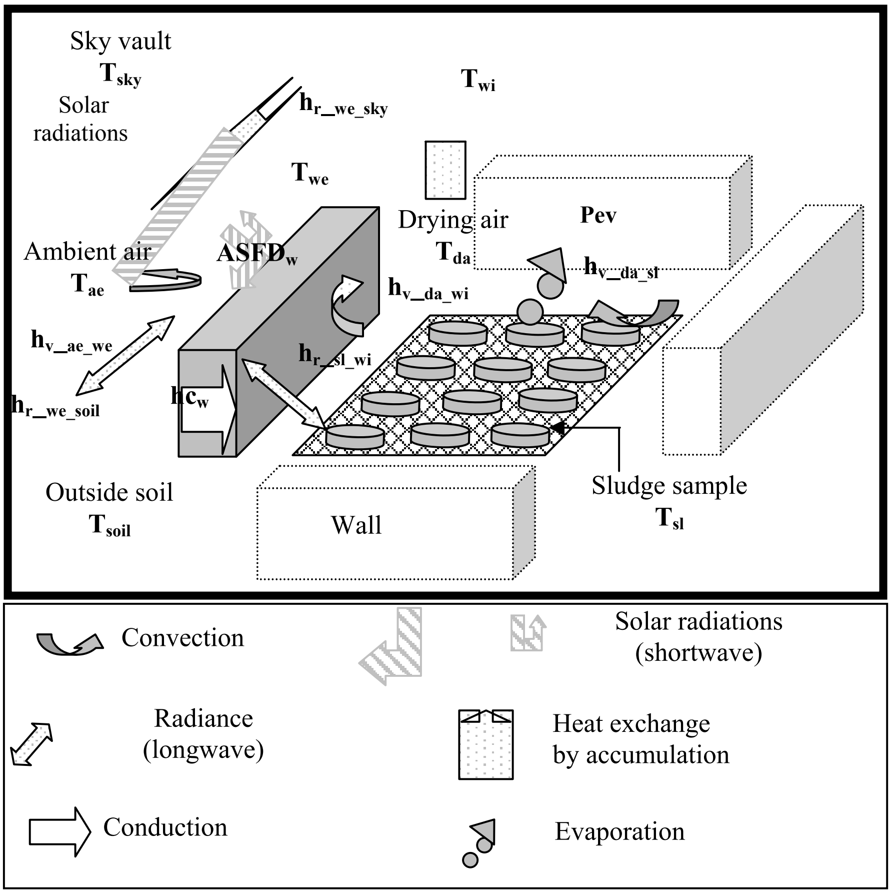


Fig. 3. *Equivalent electric circuit related to the i-th fictitious representative slice of the drying room*

Solar collector modelling

Functional and architectural description of the dryer

In the present study, the developed model corresponds to a plane collector (Fig. 4). This kind of model is often used in active drying [3].

On the basis of analogy between electric and thermal factors, an electric circuit equivalent to all the thermal exchanges occurring with this sub-area slice is shown on Fig. 5.

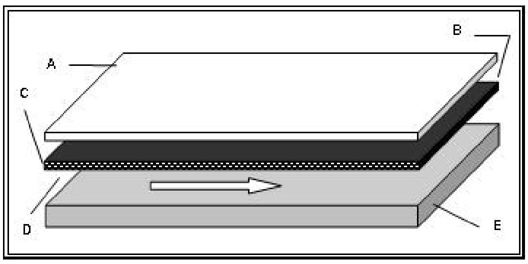


Fig. 4. *Schematic drawing of the studied solar collector*

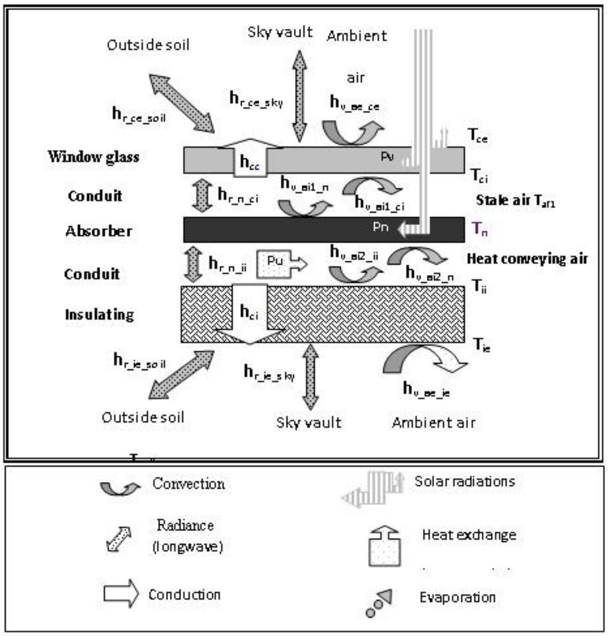


Fig. 5. *Schematic description of thermal exchange phenomena taking place at the i-th fictitious representative slice of the solar collector*

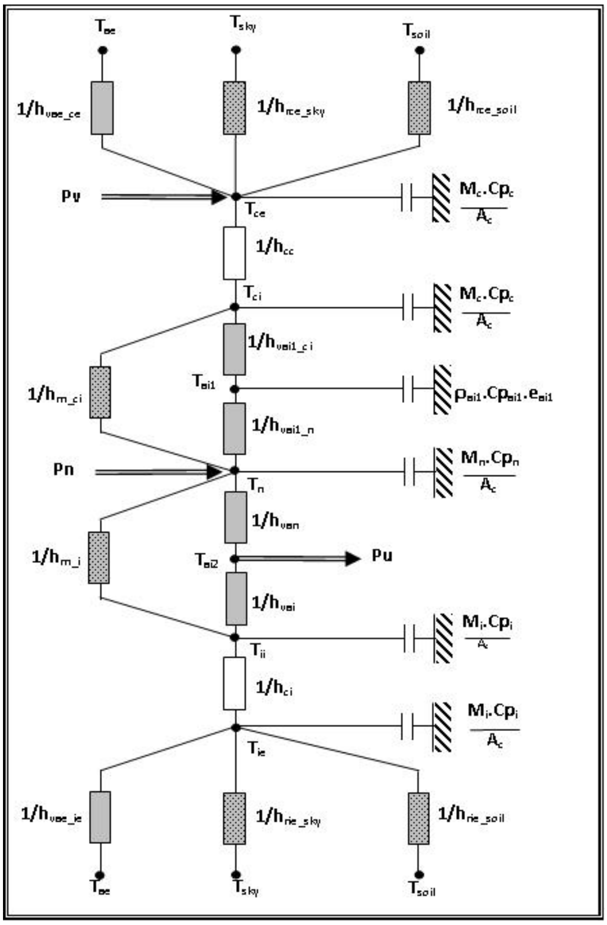


Fig.6. *Equivalent electric circuit related to the i-th fictitious representative slice of the solar collector*

By applying Ohm's law to every node of the circuit, we derive a non-linear system of six partial derivative equations. The equations are same shape as equation (1). Equivalent electric circuit related to the *i*-th fictitious representative slice of the solar collector is represented in Fig. 6.

Model of the kinetics of drying sewage sludge

The model of sewage sludge drying kinetics, which was used for the system modeling, was proposed by Léonard et al. [4]. This model takes in account the existence of two critical values of product moisture content: W_{crit1} and W_{crit2} [$kg_{water} \cdot kg^{-1}{}_{dry\ matter}$], which subdivide the sludge volumetric shrinkage curve into three distinct zones. Thus, the cross-sectional mass flux F_m has three expressions:

– Constant drying-rate period: $W > W_{crit1}$

$$F_m = F_{\text{const}} = \frac{A_0}{S} k_c \rho_a \left(Y_{sat}\left(T_w\right) - Y_\infty\right). \qquad (2)$$

– First decreasing drying-rate period: $W_{crit1} > W > W_{crit2}$

$$F_m = F_{\text{const}} = \left(\frac{V(W)}{V_0}\right)^{2/3}. \qquad (3)$$

– Second decreasing drying-rate period: $W < W_{crit2}$

$$F_m = F_{\text{const}} = \left(\frac{V\left(W_{crit2}\right)}{V_0}\right)^{2/3} \left(\frac{W}{W_{crit2}}\right)^{\alpha}, \qquad (4)$$

where α is a tuning parameter that is dependent on the drying conditions.

Experimental set up and simulation

An experimental solar dryer has been set up in a treatment plant at Reunion Island (21°S, 55°E) (Fig.7), under a tropical humid climate. The meteorological conditions used are showed below (Fig. 8).

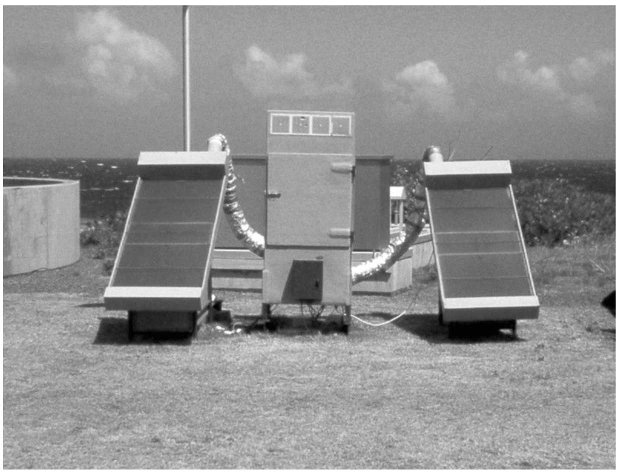


Fig. 7. *Solar dryer in the treatment plant*

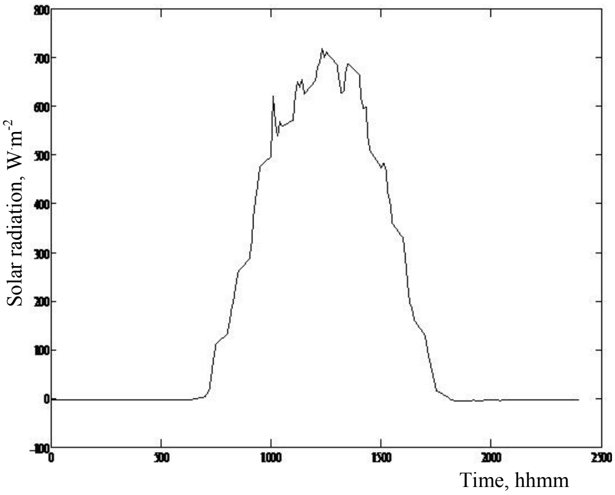


Fig. 8. Global solar irradiance during the day

The first objective is to follow the behaviour of the solar collector according to the heat conveying air flow but also to highlight the efficiency according to the solar radiation from weather conditions database.

According to the Fig. 9, the increase in useful output, collected on the outlet side of the solar collector, does not give a positive effect on the gain of air temperature when the flow increases. Indeed more the flow is raised, less the heat conveying air will not have time to recover the heat by convection.

The useful output (Fig. 10) increases with the solar radiation. However the diffuse radiation has more influence than the direct radiation on the useful output. More the solar radiation increases more the efficiency of the solar collector decreases (Fig. 11). Nevertheless the minimal efficiency is superior at 45 %.

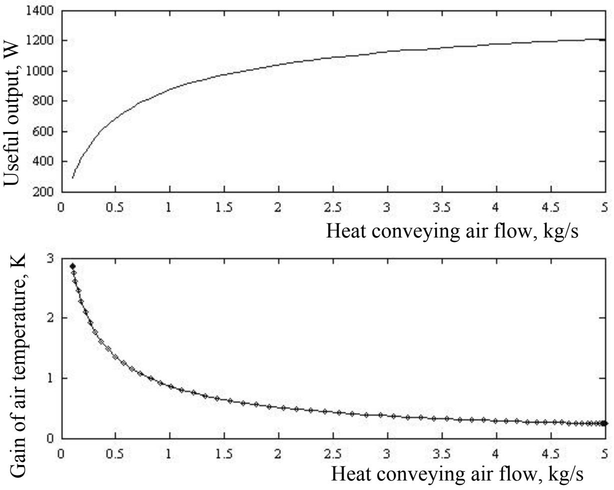


***Fig. 9.** Influence heat conveying air flow on the useful output and on the gain of air temperature*

The useful output (Fig. 10) increases with the solar radiation. However the diffuse radiation has more influence than the direct radiation on the useful output. More the solar radiation increases more the efficiency of the solar collector decreases (Fig. 11). Nevertheless the minimal efficiency is superior at 45 %.

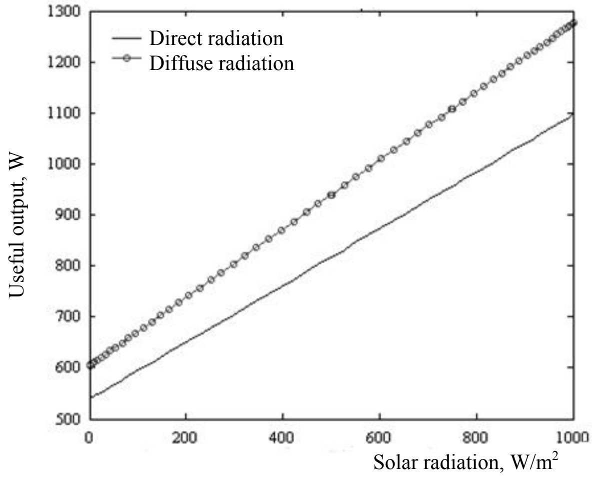


***Fig. 10.** Influence solar radiation on the useful output*

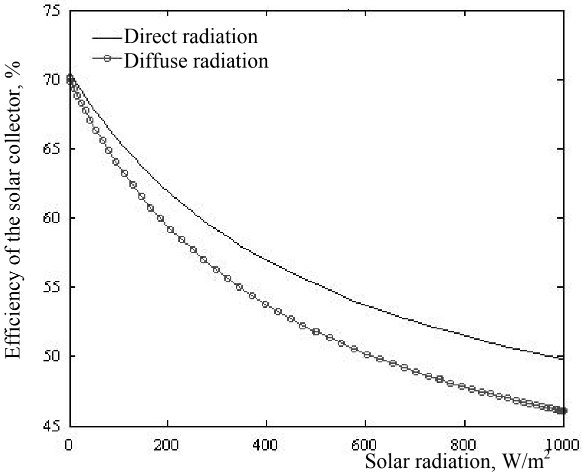


***Fig. 11.** Influence solar radiation on the efficiency of the solar collector*

The wind, as the solar radiation, has an influence on the useful output and on the efficiency of the solar collector (Fig. 12). But effects are less important. The losses are tiny. On the other hand the surface of the solar collector has a considerable influence on the parameters (Fig. 13).

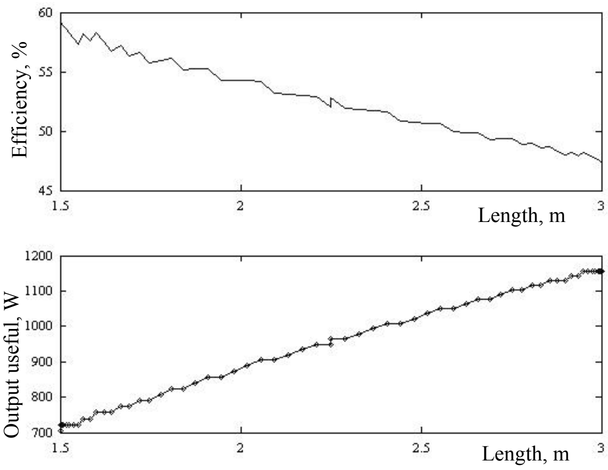


***Fig. 12.** Influence of the wind speed on the efficiency of the solar collector and the output useful*

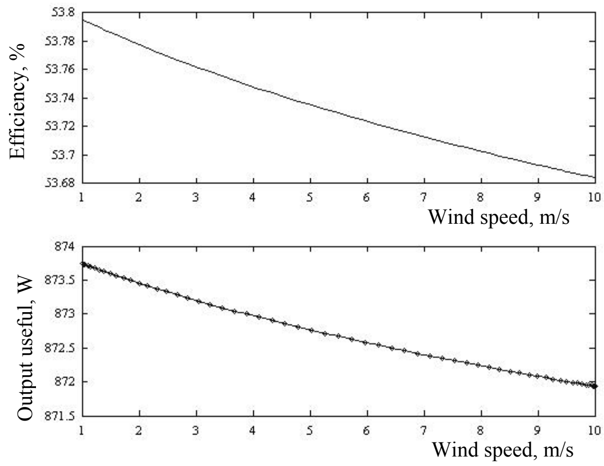


***Fig. 13.** Influence of the length of solar collector on the efficiency and the output useful*

Multiplying by two the length of the solar collector decreases by 10 % the efficiency of the solar collector.

Results of experiments

The kinetics of drying (Fig. 14) has been studied while drying 24 kg of sludge (6 kg·4). The samples have been numbered in ascending order as a function of their position in the trays.

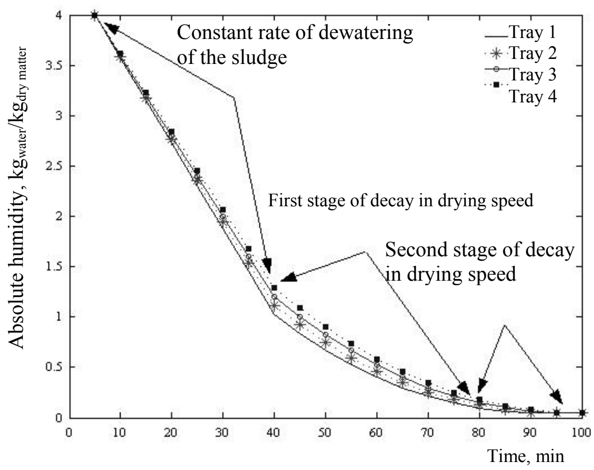


***Fig. 14.** Kinetics of drying*

Experimental characteristics

Experimental characteristics are showed in Table 1.

We can note from Fig. 14 that:

− Sludge samples dry faster at lower levels within the drying room. The greater the increase in draining air within the drying room, the higher the rate of moisture increase. The drying power of the air gradually decreases as it moves along the trays.

− During the first 40 % of the drying time, the drying rate of the sludge is constant; it is independent free of evaporated water. After this stage, we can observe the first stage of decay in the rate of drying, where steam–water exchanges reduce slowed. The difference in the moisture content of samples on Trays 1 and 4 becomes significant. After 80 % of the drying time, the drying rate decreases for a second time. During this stage, the sludge approaches a hygroscopic balance. The flux mass transfer decreases over the period of drying time. At this stage, water molecules within the samples are not free as in the first stage, but are linked with others molecules via intracellular connections. This water is termed "Water linked". To break these molecules much more energy and time are required.

Table 1

Characteristics of the sludge and drying conditions

Shape	Cylindrical
Thickness, cm	1
Diameter, cm	6
Dry matter, g/l	1.62
Volatile matter, g/l	1.38
Relative humidity of the incoming air, %	60
Relative humidity of the outgoing air, %	20
Drying temperature, °C	60

− At the end of the drying time, the four curves concur perfectly after having deviated for the major part of the drying time. The reason for this trend is as follows: once Tray 1 samples had dried, the steam pressure of water in the air is saturated when it arrives at the level of Tray 2, and the drying power of the air is reduced. Consequently, sludge on Tray 2 will exhibit the same behaviour as sludge on Tray 1 and will dry until reaching the moisture of balance. The same applies to Trays 3 and 4.

This study of the kinetics of drying led us to follow the evolution of the flow of mass according to the absolute humidity (Fig. 15).

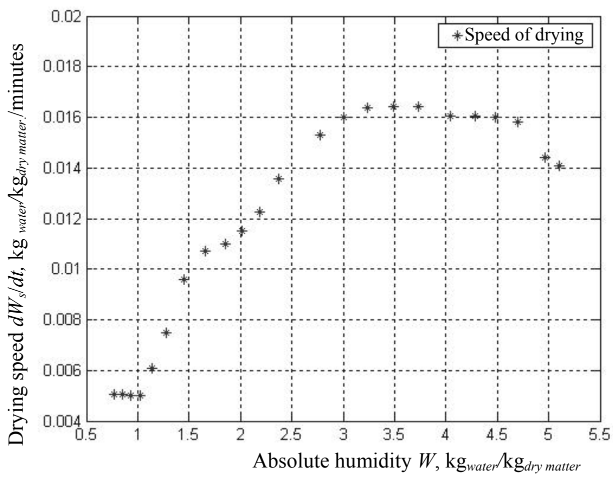


***Fig. 15.** Kinetics of drying according to absolute humidity*

This study of the kinetics of drying led us to follow the evolution of the flow of mass according to the absolute humidity (Fig. 15).
The two critical values of the absolute humidity are:

$$\begin{cases} W_{crit1} = 3 \cdot \mathrm{kg}_{water} / kg_{dry\,matter} \\ W_{crit2} = 1.1 \cdot \mathrm{kg}_{water} / kg_{dry\,matter} \end{cases}$$

The existence of these two critical values of absolute humidity arises from the fact that sludge is a hygroscopic product. In general, these values depend on the speed of drying and dimensions of the product, as well as mechanisms of moisture migration. These characteristics increase with the increasing of the drying speed and the thickness of the product. It should also be noted that the initial absolute humidity content of the product has an influence on the value of W_{crit}. These considerations explain the fact that the absolute humidity W_{crit1} and W_{crit2} can differ from one test to another.

Sensitivity analysis

The principal objective of sensitivity analysis (SA) is to ascertain how a given output depends on its input factors, Saltelli [5].
The study concerns a one output (y) model (e.g gain of air temperature) with p input parameters $y = f(x_1, x_2, \ldots, x_p)$. The approach of the proposed parametric sensitivity lays on FAST method (acronym of Fourier Amplitude Sensitivity Test) which has been developed for the first time by Cuckier and al. [6]. It consists in a first step of making several simulations modifying each parameter x_h, so that each of them includes a periodical function G_h characterised by a frequency w_h (distinct for each parameter). The frequency is the "signature" of the parameter. The Fourier coefficients corresponding to each frequency (and their harmonics) leads to the estimation of their influence.
So the sampling of the parameter x_h can be expressed by the following formula:

$$x_{h,\,k} = G_h(\sin(w_h s_k)). \tag{5}$$

The transformation function G_h is generally chosen to assure a good representation of the wide range of parameters (a good "cover"). That means that the variable x_h has to be sampled following a precise given density probability (corresponding to the uncertainty on its value). Mara et al. [7] proposed to sample the parameters with the following manner:

$$x_{h,\,k} = x_{h,0} + \delta_h \sin(w_h s_k) \quad \text{with } s_k = 2\pi k/N_s, \tag{6}$$

where k represents the simulation number ($k = 1, N_s$), $x_{h,0}$ is the basis value of the parameter h and δ_h is chosen such as $x_{h,k}$ Є $[x_{h,0} - \delta_h,\ x_{h,0} + \delta_h]$, N_s is the number of simulations. Mara [7] has shown that it is possible to represent the model output by polynomial regression based on the most important parameters of the model, as described in the following equation:

$$y_k = \beta_0 + \underbrace{\sum_{h=1}^{p} \beta_h \sin(w_h s_k)}_{\text{Term 1}} +$$

$$\underbrace{+\sum_{h=1}^{p}\sum_{h'=1}^{p} \frac{\beta_{hh'}}{2}\left[-\cos((w_h + w_{h'})s_k) + \cos((w_h - w_{h'})s_k)\right]}_{\text{Term 2}}. \tag{7}$$

The term 1 corresponds to the linear effects of the parameters (the Fourier coefficients δ_h = standard linear regression coefficient).

$$\beta_h = \frac{2}{N}\sum_{k=o}^{N} y \sin(w_h s_k). \tag{8}$$

The term 2 corresponds to the non linear effects including the interactions between two parameters x_h and $x_{h'}$ and also the quadratic effects of x_h.

$$\beta_{hh'} = -\frac{4}{N}\sum_{k=0}^{N} y \cos((w_h + w_{h'})s_k) =$$

$$= \frac{4}{N}\sum_{k=0}^{N} y \cos((w_h - w_{h'})s_k). \tag{9}$$

The interactions between the parameters produce additional frequencies with the same magnitude. So a one order interaction causes the apparition of two frequencies which are $|w_h - w_{h'}|$ and $|w_h + w_{h'}|$.
More precisely, to determine the surface response of the studied model, Mara [8] proposed a method. The following steps of this approach are described beneath:

− Sampling of the parameters of the model in their respective range of variation. A distinct frequency is attributed to each parameter and the simulations are made.

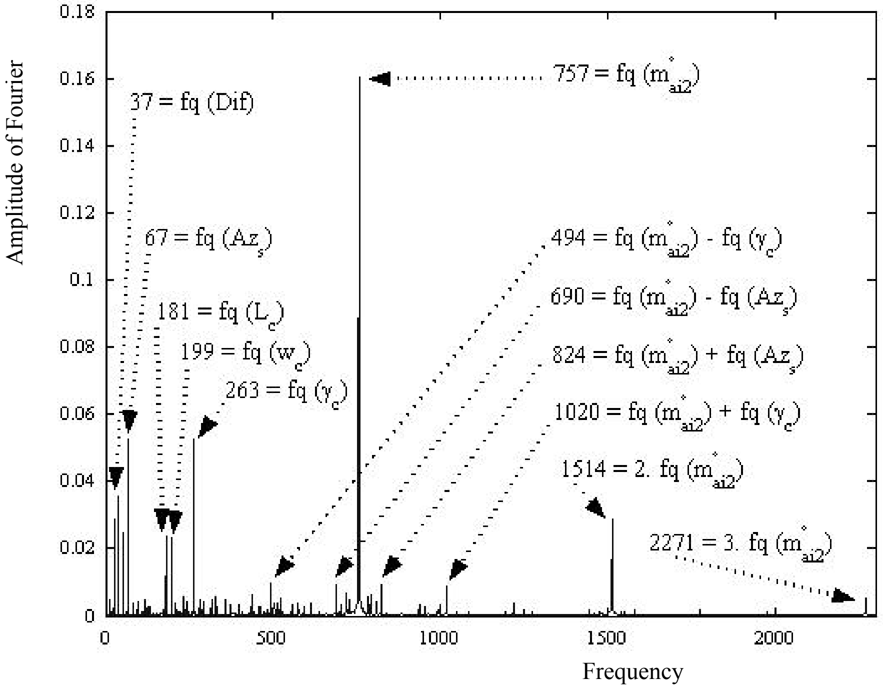
− The Fourier transform calculation of the output of the model y : the spectrum drawing:
We identify the frequencies which appear at each step of our exploration in order to determine the "metamodel" components.

− βi coefficients values estimation using the relations (8-9) or by using an optimisation algorithm.

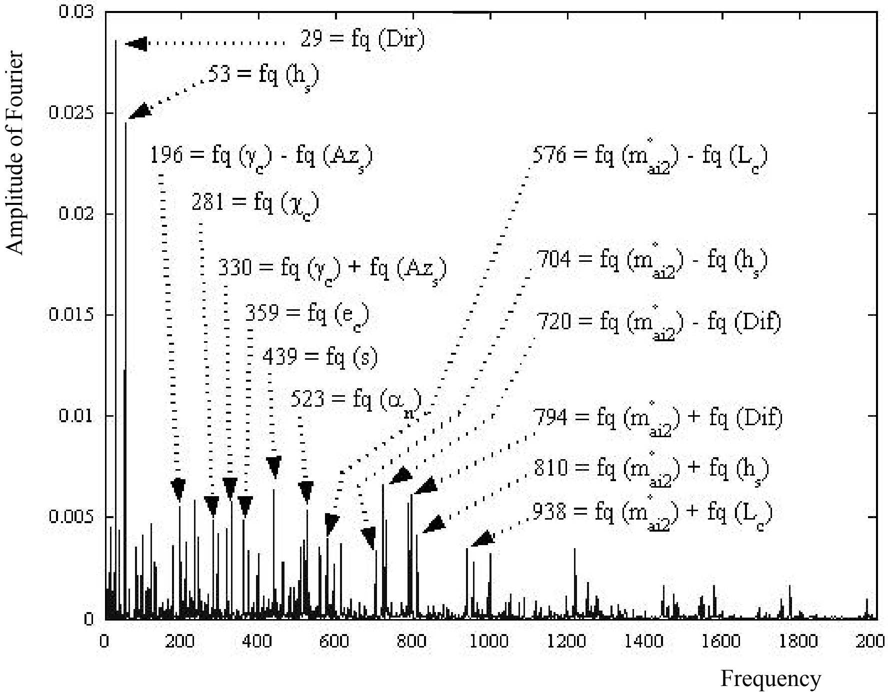
− Analysis of the residue or correlation coefficient R^2 calculation to appreciate the validity of the identified response surface.

− Comparison of the linear regression coefficients to determine the effects of the parameters on the output of the model.

Such an approach is an element of validation of our model. Fig. 16 shows the results of the FAST method used to determinate the most important parameters. In this step, the parameters studied are the structural and functional parameters of the model, as described in Table 2.
It is important to notice that the SA method of used is a local method. In this way, the range of variation used, approximately 10 % of the optimal value is the domain of validity.



a



b

***Fig. 16.** The results of the FAST method: a – identification according to their frequency of the influential parameters; b – zoom*

This spectral analysis (Fig. 16) has showed that the influential parameters on the heat conveying air were: the flow, the structural parameters of solar collector (length and width), but also the meteorological conditions, azimuth and height of the sun, absorption coefficients of the absorber which represent the reality of influence of solar energy in a solar collector model.

This analysis allows us to determine a polynomial of regression corresponding to an output of the solar collector model that is the gain of heat conveying air temperature.

The "metamodel" is presented by equation (10). The polynomial regression is obtained by optimizing the coefficient using a Levenberg Marquart algorithm

$$\Delta T_{air} = 0.866 - 0.03\langle T_{ae}\rangle + 0.053\langle Dir\rangle + 0.066\langle Dif\rangle + $$
$$+ 0.011\langle \alpha_n\rangle + 0.007\langle \alpha_{nd}\rangle + 0.109\langle AZ_s\rangle + 0.047\langle L_c\rangle - $$
$$- 0.291\langle m_{ai2}\rangle - 0.010\langle \chi_c\rangle - 0.110\langle \gamma_c\rangle . \qquad (10)$$

Table 2
Frequency associated to the input parameters of the solar collector model

Factors	Range of variation	$x_{h,0}$	Frequency
Dif	[200; 400]	300	37
Dir	[600; 800]	700	29
AZ_s	[-180; 180]	15	67
L_c	[1.5; 3]	2	181
w_c	[0.9; 1.1]	1	199
α_n	[0.8; 0.99]	0.91	523
m_{ai2}	[0.8; 1]	0.9	757
χ_c	[24; 26]	25	281
e_c	[0.003; 0.005]	0.004	359
k_c	[1; 1.2]	1.08	373
γ_c	[-180; 180]	90	263
ε_c	[0.8; 0.95]	0.88	397
α_{nd}	[0.7; 0.95]	0.9	557
K_{is}	[0.042; 0.044]	0.043	641
ε_{is}	[0.8; 0.95]	0.89	673
s	[20; 22]	21	439

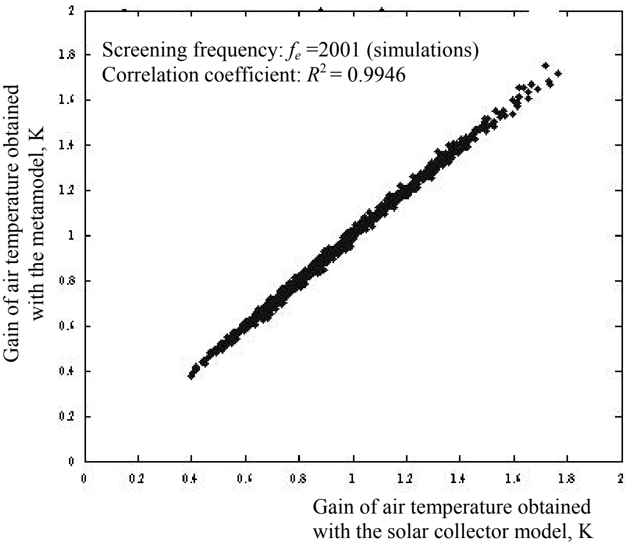


Fig. 17. *Comparison between results simulated with metamodel and the solar collector model*

The comparison of results (Fig. 17) obtained between the metamodel and the solar collector model gives a correlation coefficient equivalent to 0.9946. The metamodel proposed gives satisfaction. As a result the metamodel becomes an alternative for the modelling. The most influential variables can be identified by comparing the regression coefficients of the linear terms of the metamodel. The results of such a comparison are presented in Fig. 18, in which a positive effect of a parameter indicates that an increase in its value entails an increase in the value of the observed output parameter. A negative effect indicates that an increase in the parameter value results in a decrease in the value of the chosen output parameter (Fig. 18).

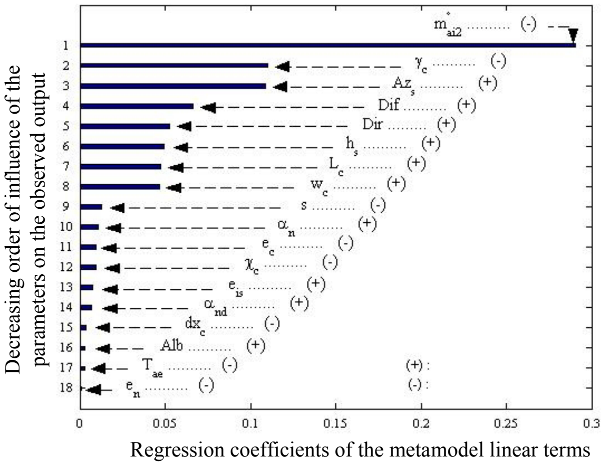


Fig. 18. *Comparison of the regression coefficients of the 18 most influential parameters of the solar collector model*

Conclusion

The objective of this wok was to model the solar drying active system using equations of thermal balance. But also, used sensitivity analysis in order to determine influential parameters on the output model and prove this method could be an alternative to traditional modelling method. The main advantages of this approach compared to conventional are simplicity and speed.

The accuracy of the metamodel obtained is fine considering that the comparison with the model give a good correlation coefficient. The metamodel brings a fine approximation of the solar collector behavior. In this case of this we focus on meteorological conditions, functional and architectural parameters of the solar collector.

This work highlighted the drying speed of sludge and characterized the kinetics of drying via the determination of hygrometric parameters. Further research in this field will consist in a study of the incineration of sludge with or without the addition of household waste.

Acknowledgement

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Nomenclature

Key to abbreviations

A_0: sample initial exchange area, m^2
Alb: albedo
ASFD: absorbed solar flux density, $W \cdot m^{-2}$
AZ_s: azimuth of the sun, °
C_k: heat capacity, $J \cdot K^{-1}$
C_{kj}: coefficient of conductive heat exchange between the k and j nodes, $W \cdot K^{-1}$
C_p: mass heat capacity, $J \cdot K^{-1} \cdot kg^{-1}$
Dif: diffuse solar irradiance in the plane of the collector, $W \cdot m^{-2}$
Dir: direct solar irradiance in the plane of the collector, $W \cdot m^{-2}$
e: thickness, m
F_{const}: cross-sectional mass flux during the constant drying-rate period , $kg \cdot m^{-2} \cdot s^{-1}$
H_{kj}: coefficient of convective heat exchange between the k and j nodes, $W \cdot K^{-1}$
hc: conduction heat coefficient, $W \cdot K^{-1} \cdot m^{-2}$
hr: radiance heat coefficient, $W \cdot K^{-1} \cdot m^{-2}$
h_s: angular height of the sun, °
hv: convection heat coefficient, $W \cdot K^{-1} \cdot m^{-2}$
k_c: external mass transfer coefficient, $m \cdot s^{-1}$
L_c: solar collector length, m
M: mass, kg
m_{ai2}: heat conveying air flow, $kg \cdot s^{-1}$
Pev: product humidity evaporation heat density, $W \cdot m^{-2}$
Ploss: heat loss density, $W \cdot m^{-2}$
R_{kj}: coefficient of long wave radiation heat exchange between the k and j nodes, $W \cdot K^{-1}$
S: surface, m^2
s: inclination of the solar collector, °
T: temperature, K
T_w: wet bulb temperature, K
V: sample instantaneous volume, m^3
V_0: sample initial volume, m^3
W: sample humidity content, $kg_{\mathrm{water}} \cdot kg^{-1}{}_{\mathrm{dry\ matter}}$
W_c: solar collector width, m
$Y_{sat}(T_w)$: air saturation humidity at wet bulb temperature, $kg_{water} \cdot kg^{-1}{}_{dry\ air}$
Y_∞: bulb external gas phase humidity, $kg_{water} \cdot kg^{-1}{}_{dry\ air}$

Key to subscripts

ae: ambient air
*ai*1: stale air
*ai*2: heat conveying air
c: window glass
ce: external face of window glass
ci: internal face of window glass
da: drying air
ie: external face of insulating
ii: internal face of insulating
is: insulating
n: absorber
sl: sludge sample
sky: sky vault
soil: outside soil
w: drying room wall
we: external face of the drying room wall
wi: internal face of the drying room wall

Greek symbol

α_n: absorption coefficient direct irradiance of absorber
α_{nd}: absorption coefficient diffuse irradiance of absorber
β: coefficients of polynomial regression
ε: emissivity
χ_c: extinction coefficient, m^{-1}
γ_c: orientation of the solar, °
ρ_a: density of humid air, $kg \cdot m^{-3}$
σ_k: heat source, W

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