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An Overview on Application of Exergy and Energy for Determination of Solar Drying Efficiency

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Abstract The main objective of this work is to give an overview of the different used mathematical methods for modeling and calculating the energy and exergy efficiency of a solar drying system. For determination of the energy efficiency of thin or thick layers, heat and mass balances are established to the different components. In the case of thick layers equations of porous media are used. These methods allow following, in particular, the variations of the heated air and the product temperature and humidity. As a second part, the common way for the calculus of the exergetic efficiency passes through the establishment of exergy balance and after calculating the input, output and exergy loss. The influence and illustration of several parameters are as well presented in this paper.

Keywords Solar Air Collector, Drying Chamber, Energetic Efficiency, Exergy Efficiency, Mathematical Modelling

1. Introduction

Drying constitutes an important process for a large variety of industries. For example, for foodstuffs, it is a necessary step for the preservation of the final product or to make it ready to be stored[1-4]. On the other hand and for other materials, such as woods, concretes, bricks and sludge, the passage by this process is an obligation to make these products marketable[5-8]. As it is well known, drying is the most energy intensive operation of the industrial processes. In most industrialized countries, between 7 and 15% of a nation's industrial energy is used for drying[9]. Other estimations report that national energy consumption for industrial drying operations are ranging from 10 to 15% for United States, Canada, France and United Kingdom and reach 20 to 25% for Denmark and Germany[10]. Furthermore, around 35 % of the consumed energy in drying is used for paper and pulp industry and only 5% are used for chemicals[10]. The resulted high cost of this unit operation directed the efforts of the Scientifics to look for alternative cheap sources of energy, in particular free solar energy. Coupling the two ideas gives birth to several types of solar dryers. In general manner, solar dryers are classified into active and passive dryers and each classification is divided into direct, indirect and mixed mode type[11-13]. However and in order to face the intermittent character of solar energy, developed systems can be dotted with a second source of energy using electrical heater[1, 14] or storage systemsfilled with packed rock-beds[15-17], gravels[18], desiccants[19], water[20] or phase change material[21-23]. We cannot have an optimum use and design of a solar dryer without passing through simulation and the mathematical modelling. The existing models are taking essentially two ways: the first approach studies particularly the behaviour of the product during the process represented by the drying kinetic. These developed models agree to calculate several parameters such as coefficient of diffusion, heat and mass coefficients and drying constants[5, 24-35]. The second approach studies the general behaviour of the solar dryer by applying heat and mass transfers. It allows following variations of temperature and humidity of both the dried product and the heated air. But also it permits following the different temperatures and other parameters of the solar collector and the drying chamber. By this method, efficiency of the studied system can be easily obtained. In this paper, we are focusing on this second approach.

In this last decade, exergy is introduced as an important and a powerful analysis tool for design and calculus of the performances of thermal systems. From a thermodynamic point of view, exergy is defined as the maximum amount of work which can be produced by a quantity or flow of matter, heat or work as it comes to equilibrium with a reference environment[36]. Exergy starts finding applications in several industries and we direct our attention to the application for drying process[37-44].

Therefore, the aim of this paper is to present a review about the application of exergy and energy to solar drying with presentation of the different mathematical models that treat the general behaviour of the drying systems and calculate their energetic and exergetic efficiencies with

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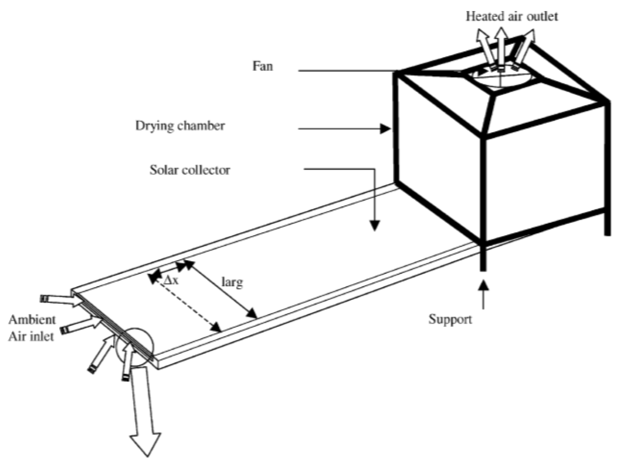
products packed in thin or thick layers.

2. Energy Analysis

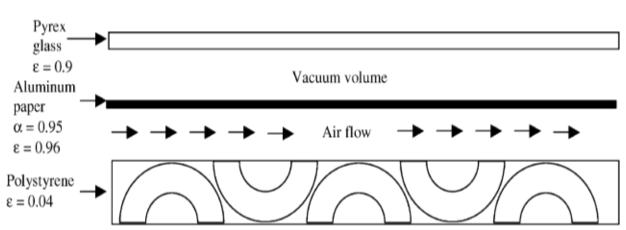
2.1. Solar Drying of Thin Layers

We will apply our study to a representative simple convective solar dryer, represented in Figure 1a. It is constituted of two parts; a simple flat solar air collector (Figure 1b). It is composed of an aluminium plate used as an absorber, covered from the above by a glass plate and insulated from the exterior using polystyrene. There is a vacuum space between the absorber and the glass cover. The second part concerns the drying chamber made with bricks insulated from the exterior by polystyrene and can support trays where the product is putted. Forced convection is obtained using a fan which permits to have a homogeneous distribution of the heated air inside the drying chamber; also it allows having better control of the process[1, 11].

One of the frequent models used to study solar drying of thin layers (putted in perforated trays), is: step by step method[1, 13, 45]. It consists on taking a fictitious slice that can be noted “j”, applying heat and mass balance to this slice, then generalizing the study to all the system by varying the step “j”. This method is applied to both the solar collector (Figure 1b) and the drying chamber (Figure 2).



(a)



(b)

Figure 1. (a) Global diagram of a solar dryer. (b) Step “j” of the flat plate solar air collector[1]

2.1.1. Application to the Solar Collector

A heat balance is established for the different components; which are the interior and exterior side of the glass cover, the absorber, the interior and exterior side of the insulator, resumed by Equation 1 and Table 1:

Table 1. Definitions and values of the different used indices and parameters at application of heat balance to different components of the solar collector

n °	Part of application	Definitions and values
1	Glass exterior side	i: glass exterior side j: skier vault k: ambient environment l: glass interior side q_1: flux of energy stored by the glass $q_2 = q_3 = 0$
2	Glass Interior side	i: glass interior side j and k: absorber l: glass exterior side $q_1 = q_2 = q_3 = 0$
3	Absorber	i: glass interior side j and k: absorber $k_{i,l} = 0$ q_1: flux of energy absorbed by the absorber $q_2 = h_{fld,A}(T^*-T_A)$; exchange by convection between the absorber and the heated air $q_3 = hr_{I,A}(T_{I,i}-T_A)$; exchange by radiation between the absorber and the interior side of the insulator
4	Insulator interior side	i: interior side of the insulator j: absorber k: heated air l: exterior side of the insulator $q_1 = q_2 = q_3 = 0$
5	Insulator exterior side	i: exterior side of the insulator j: ground k: ambient environment l: interior side of the insulator $q_1 = q_2 = q_3 = 0$

$$\frac{m_i Cp_i}{Surf}\left(\frac{dT_i}{dt}\right) = hr_{i,j}\left(T_j - T_i\right) + h_{i,k}\left(T_k - T_i\right) + k_{i,l}\left(T_l - T_i\right) + q_1 + q_2 + q_3 \tag{1}$$

Also, the air flowing between the absorber and the insulator is written in the following form:

$$\dot{m}_{am} . Cp_{air}\left(T - T^*\right) = surf\ .\ h_{air,\ A} \cdot \left(T_A - T^*\right) + surf\ .\ h_{air,\ I} \cdot \left(T_{I,\mathrm{int}} - T^*\right) \tag{2}$$

The resolution of the obtained system composed of six differential equations, using any adapted method such as the iterative method of Gauss-Seidel[1], allows calculating the temperature of exit from the solar collector, necessary for the calculus of its efficiency.

The efficiency of a solar collector is generally calculated using the subsequent equation[46-49]:

$$\eta = \frac{\dot{m}Cp\int_{t1}^{t2}\left(T_o - T_i\right)dt}{A_c\int_{t1}^{t2} I_t dt} \tag{3}$$

transformed by Hottel-Whiller-Bliss, for the steady state case and rewritten in the following form:

$$\eta = \frac{Q_u}{A_c I_t} = F_R(\tau\alpha) - F_R U_L \frac{T_i - T_\alpha}{I_T} \qquad (4)$$

Where:

F_R is the heat removal factor of solar collector, calculated:

$$F_R = \frac{\dot{m}Cp}{A_c U_L}\left(1 - \exp\left(A_c U_L F' / \dot{m}Cp\right)\right) \qquad (5)$$

And:

U_L is the global heat loss coefficient, written:

$$U_L = \frac{I_{th}(\tau\alpha)}{(T_i - T_o)} \qquad (6)$$

This approach is widely used for experimental works as it needs to know only geometric parameters of the solar collector and just inlet and outlet temperatures which can be easily obtained using thermocouples.

Studies have shown that performances of a solar collector, represented by its outlet air temperature and its efficiency, depend on several parameters like the region where the collector is installed[45], depend on their internal parameters, such as its surface (Figure 2) and the exterior conditions like the temperature and the velocity of the ambient air[35, 45]. These performances vary with time and have a general behavior as the total received radiations (Figure 2).

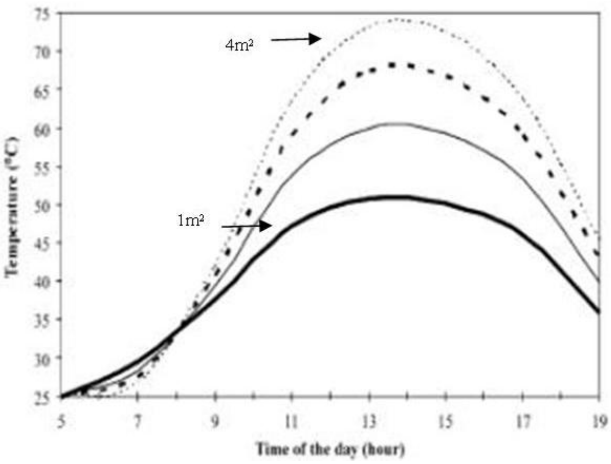


Figure 2. Influence of the surface of the collector on its outlet air temperature[1]

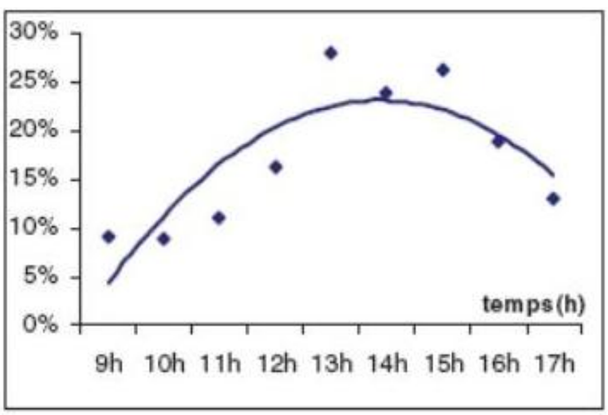


Figure 3. Variation of the efficiency of a solar collector with time[48]

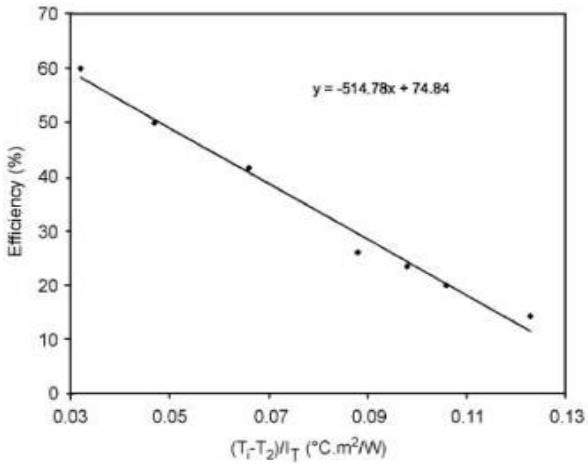


Figure 4. Collector efficiency with $(T_i\text{-}T_a)/I_T$[46]

Consequently, the efficiency of a solar collector varies in time (Figure 3) and depends strongly on the absorbed radiations and collector outlet temperature (Figure 4). The values of the efficiency are variable and can reach 60%.

2.1.2. Application to the Drying Chamber

A step ``j`` of the drying chamber is shown in Figure 5.

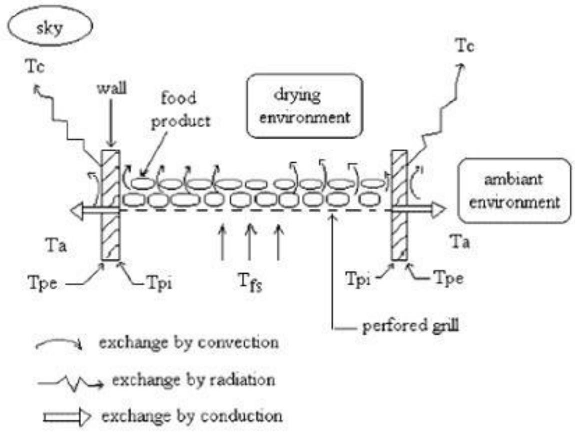


Figure 5. Step "j" of the drying chamber[50]

Heat balance is established between the heated air, the product and the interior face of the brick wall leading to:

$$\dot{m}_{ach} \cdot Cp_{air}\left(T^*_{ach} - T_{ach}\right) = h_{ach,\,f}\, S_f \cdot \left(T_{ach} - T_f\right) + h_{ach,\,pi}\, S \cdot \left(T_{ach} - T_{pi}\right) \qquad (7)$$

S_f represents the exchange surface between the total surface of the product and the air. It is given as a function of the dimensions of the product and its number[1, 13].

The other exchanges can be represented by the next equation and table 2.

$$\frac{m_i Cp_i}{S}\left(\frac{dT_i}{dt}\right) = hr_{i,j}\left(T_j - T_i\right) + h_{i,k}\left(T_k - T_i\right) + k_{i,l}\left(T_l - T_i\right) + q \qquad (8)$$

However, the exchanges between the brick and the polystyrene wall are given by:

$$\frac{m_p Cp_p}{S}\left(\frac{dT_p}{dt}\right)+k_p\left(T_p-T_{pe}\right) = \frac{m_b Cp_b}{S}\left(\frac{dT_p}{dt}\right)+k_b\left(T_p-T_{pi}\right) \tag{9}$$

Table 2. Definitions and values of the different used indices and parameters at application of heat balance to different components of the drying chamber

n °	Part of application	Definitions and values
1	Product	i: product $hr_{i,j} = k_{i,l} = 0$ k: heated air q = -Pev
2	Internal Surface of the brick wall	i: brick interior side $hr_{i,j} = 0$ k: heated air l: brick exterior side q = 0
3	Insulator exterior side	i: exterior side of the insulator j: skier vault k: ambient air l: interior side of the insulator q = 0

Pev is the evaporative power given as a function of the mass and the drying kinetic of the studied product.

The resolution of this system of differential equations allows calculating the different changing parameters inside the drying chamber especially the variations of the temperatures of the product and the air for the several horizontal trays. By this method, drying chamber efficiency can be calculated, well known as pick up efficiency, written[51-53]:

$$\eta=\frac{W}{\rho Vt\left(h_{as}-h_i\right)} \tag{10}$$

This parameter determines the efficiency of moisture removal by the drying air from the product.

The obtained results, dealing with solar drying of multiple trays, show that the process is done with a non-homogeneous manner, as shown in Figure 6 and 7. The product putted in tray near the heating source dries faster than products putted in the other trays.

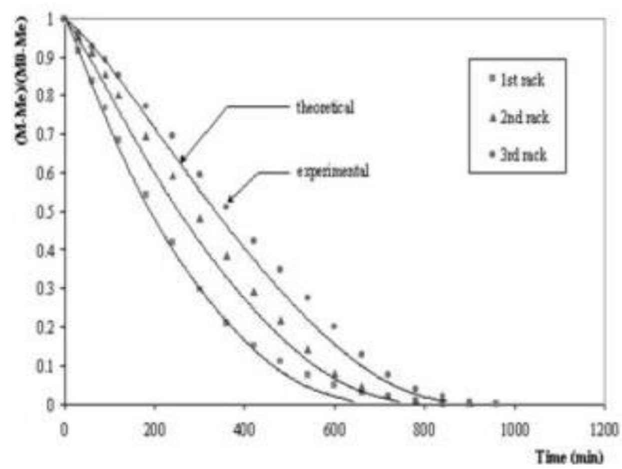


Figure 6. Evolution of the reduced content in three racks[50]

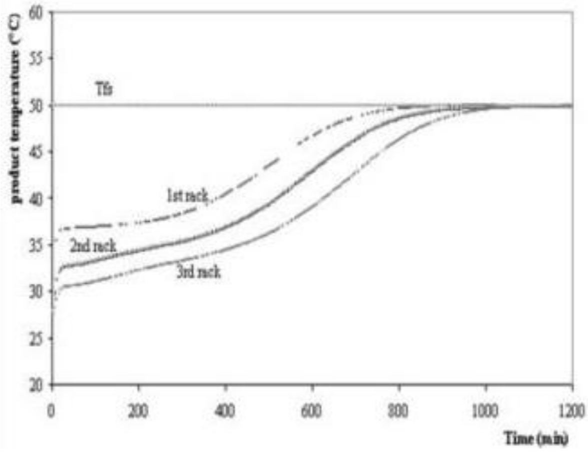


Figure 7. Product temperature profile[50]

Also some studies show that drying kinetics of the dried product and its temperature is affected[1]: by the surface of the solar collector, by the characteristic dimensions of the product, by the mass of the product putted on each tray and by the air flow rate[50].

2.2. Solar Drying of Thick Layers

The unique difference between solar drying of thin and thick layers is that, for the second case, the product is filled in multiple condensed layers. However, it does not affect the precedent study relative with the solar collector and the same mathematical procedure is used.

As the product is filled in thick layers, the drying chamber can be supposed as a porous media in the macroscopic scale. So, mathematical model describing transfer in porous media can be applied for the product, represented by the solid phase, and the heated air, presented as the gas phase. We obtain four differential equations[4, 13, 51].

Application of mass balance in gas phase:

$$\varepsilon\,\rho_f\,\frac{\partial w}{\partial t}+\rho_f\vec{V}_f\,\vec{\nabla}w-\rho_f D\nabla^2 w=\sigma_f \tag{11}$$

Mass balance in solid phase:

$$\left(1-\varepsilon\right)\rho_s\,\frac{\partial C}{\partial t}+\left(1-\varepsilon\right)\rho_s\vec{V}_s\,\vec{\nabla}C=\sigma_f \tag{12}$$

Heat balance in gas phase:

$$\left[\left(\rho Cp\right)_{app}\right]_f\left(\varepsilon\frac{\partial T_f}{\partial t}+\vec{V}_f\,\vec{\nabla}T_f\right)-k\nabla^2 T_f = hA\left(T_f-T_s\right) \tag{13}$$

Heat balance in solid phase:

$$\left[\left(\rho Cp\right)_{app}\right]_s\left(\varepsilon\frac{\partial T_s}{\partial t}+\vec{V}_s\,\vec{\nabla}T_s\right) = -hA\left(T_s-T_f\right)+H\rho_s\left(1-\varepsilon\right)\frac{\partial C}{\partial t} \tag{14}$$

With:

$$\sigma_f=-\sigma_s \tag{15}$$

Combinations of equations 11 with 12 and 13 with 14 give:

$$\varepsilon \frac{\partial w}{\partial t} + V_f \frac{\partial w}{\partial y} = D \frac{\partial^2 w}{\partial y^2} - (1-\varepsilon) \frac{\rho_s}{\rho_f} \frac{\partial C}{\partial t} \tag{16}$$

$$(\rho Cp)_{eff} \frac{\partial T}{\partial t} + (\rho Cp)_f \left[V_f \frac{\partial T}{\partial y} \right] = k_{eff} \frac{\partial^2 T}{\partial y^2} + H \rho_s (1-\varepsilon) \frac{\partial C}{\partial t} \tag{17}$$

With:

$$(\rho Cp)_{eff} = \varepsilon (\rho Cp)_f + (1-\varepsilon)(\rho Cp)_s \tag{18}$$

These equations are obtained after considering the following simplifications[51]: the walls of the drying chamber are considered as adiabatic, the product is immobile and the isotropic. Also, we consider that the air is flowing in one direction. The resolution of the differential equation system permits following the variations of the temperature and humidity for both the product and the heated air with time and the deepness of the layers. In consequence, efficiency of the drying chamber can be easily calculated using equation 10[51].

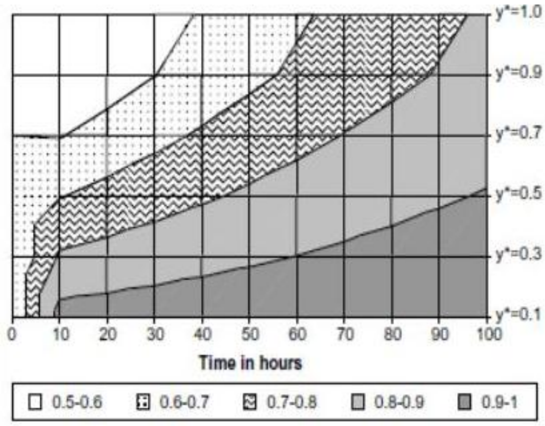


Figure 8. Variation of the temperature of the media vs. time and bed deep[51]

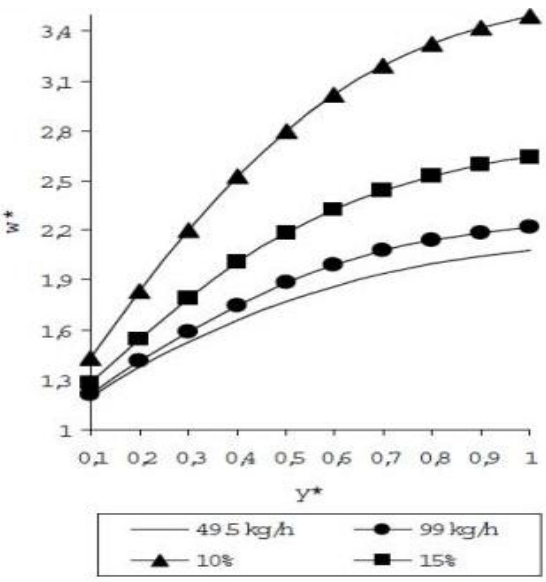


Figure 9. Influence of flow rate and initial humidity on humidity of the heated air[54]

Some studies have shown that thick layer drying is also done in a non-homogeneous manner. The temperature and drying kinetic was affected by many parameters, such as the initial humidity of the air, the flow rate and the height of the bed (Figure 8 and 9)[51, 54]. A representation of the efficiency is shown in Figure 10, with variation in time and height of the bed.

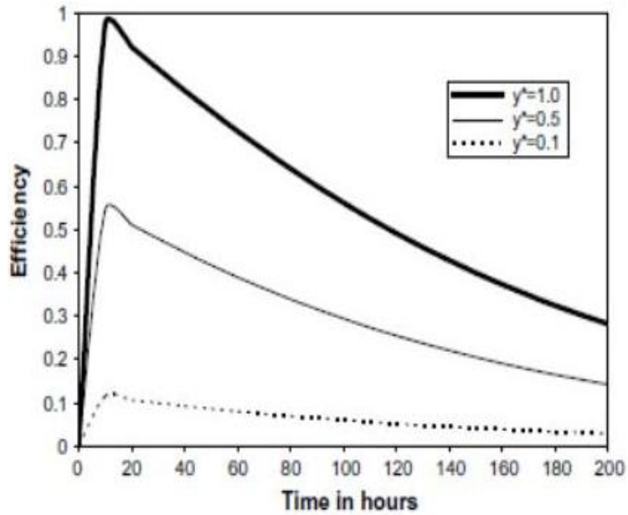


Figure 10. Variation of the pick-up efficiency during drying of thick layers[51]

2.3. System Efficiency

The system efficiency indicates the overall thermal performance of a drying system including the efficiency of a solar collector, the drying chamber and any other supplement add to the system. The global efficiency is written[52]:

For natural convection solar dryers:

$$\eta = \frac{WL}{IA} \tag{19}$$

For forced convection solar dryers that use a fan or a bowler:

$$\eta = \frac{WL}{IA + P_f} \tag{20}$$

For hybrid solar dryers that use a second source of energy, the efficiency is calculated using the next equation:

$$\eta = \frac{WL}{IA + P_f + (m_b \times LCV)} \tag{21}$$

It clear (m_b*LCV) represents the additional source of energy.

3. Exergy Analysis

Exergy is presented as a useful analysis tool in the design, assessment, optimization and improvement of energy systems, that can be applied on both system and components levels[55-56]. The exergy method can help further the goal of more efficient energy resource use, because it enables the locations, types and true magnitudes of looses to be determined. As a result, exergy analysis can reveal where and by how much it is possible to design more efficient thermal systems by reducing the sources of existing inefficiencies[49].

The second law of thermodynamics introduces the useful concept of exergy in the analysis of thermal systems. Exergy analysis evaluates the available energy at different points in a system. Exergy is a measure of the quality of grade of energy and it can be destroyed in the thermal system. The second law states that part of the exergy entering a thermal system with fuel, electricity, flowing streams of matter, and so on is destroyed within the system due to irreversibility. The second law of thermodynamics uses an exergy balance for the analysis and the design of thermal systems[49].

The general mathematical description of the exergy is presented under the following equation[48-49, 57-59]:

$$Exergy = (u_0 - u_m) - T_m(s - s_m)N + \frac{P_m}{J}(v_0 - v_m) + \frac{v^2}{2gJ}$$
$$+ (z - z_0)\frac{g}{gJ} + \sum_c (\mu_c - \mu_m)N_c + E_i A_i F_i (3T^4 - T_m^4 - 4T_m T^3) \qquad (22)$$

Where: ∞ represents the reference conditions.

The right terms of the equations are respectively: internal energy, entropy, work, momentum, gravity, chemical reactions and radiation emission.

One of the common simplifications used for equation 22 is to substitute enthalpy for the internal energy and PV. Also, the exergy is used with neglecting gravitational and momentum terms. The pressure term is neglected because the volume is almost kept constant and the operation is happening without any chemical reactions. Consequently, the equation is generally reduced to:

$$Exergy = m_a C p_a \left[(T - T_\infty) - T_\infty \ln \frac{T}{T_\infty} \right] \qquad (23)$$

3.1. Application of Exergy for Solar Collector

The most presented papers, dealing with exergy analysis of solar drying, are presenting solar dryers similar to one illustrated in Figure 1. The drying system contains a simple solar air heater, and a drying chamber that supports horizontal trays. The system can work with natural convection (without fan) or using forced convection (with fan).

In the case of application of exergy to a simple solar air collector; the terms of momentum, gravity and chemical reaction can be neglected. However, radiation emission term that depends on temperature must be kept.

The exegy loss is the difference between the exergy inlet and outlet that are respectively functions of the inlet and outlet temperatures. It is expressed:

Exergy loss = Exergy inflow-exergy outflow

Mathematically determined by equation 24:

$$\sum Ex_l = \sum Ex_i - \sum Ex_o \qquad (24)$$

The exergy inlet for the collector is stated as equation 25.

$$Ex_{ci} = m_{cai} C p_a \left[(T_{ci} - T_\infty) - T_\infty \ln \frac{T_{ci}}{T_\infty} \right] \qquad (25)$$

And the exergy outlet for the collector is written:

$$Ex_{co} = m_{cao} C p_a \left[(T_{co} - T_\infty) - T_\infty \ln \frac{T_{co}}{T_\infty} \right] \qquad (26)$$

Then the exergy of solar radiation for the collector:

$$Ex_{solar} = E_{net} \left[1 - \frac{4T_0}{3T} + \frac{1}{3}\left(\frac{T_0^4}{T}\right) \right] A_{cz} \qquad (27)$$

The exergy efficiency of a solar collector is:

Ex(efficiency) = (Ex(inflow)-Ex(loss))/Ex(inflow) (28)

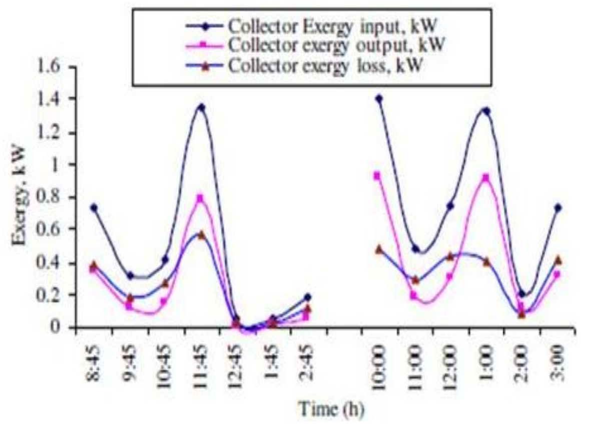


Figure 11. Variation of the collector exergy parameters with drying time[49]

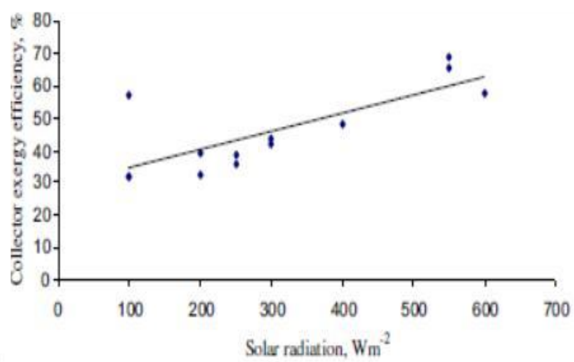


Figure 12. Variation of the collector exergy efficiency parameters with solar radiation[49]

Figure 11 shows the variations of the input, output and loss exergy for a solar collector with drying time. The general outline of the curves in influenced by the variation of the received solar radiation as they have almost the same appearance. Of course, the efficiency of the solar collector decreases with the solar radiation decrease, as shown in Figure 12.

3.2. Application of Exergy to the Drying Chamber

Based on the same way, a comprehensive procedure of the application of exergy for the drying chamber was developed[36, 60-61]. A representative scheme is illustrated in Figure 13.

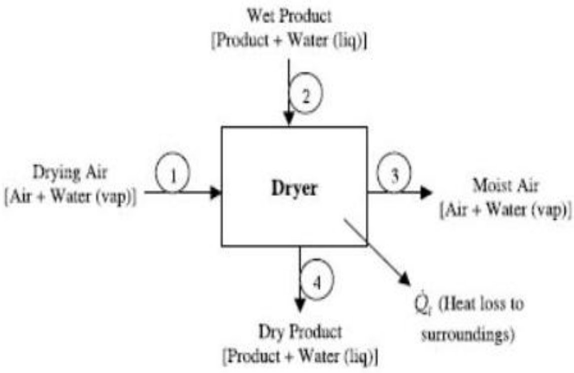


Figure 13. Schematic of a drying process showing input and output terms for the drying chamber[60-61] Exergy balance gives[60-61]:

Exergy balance gives:

$$\dot{m}_a e_1 + \dot{m}_p (e_p)_2 + (\dot{m}_w)_2 (e_w)_2 = \dot{m}_a e_3 + \dot{m}_p (e_p)_4 + (\dot{m}_w)_4 (e_w)_4 + \dot{E}_q + \dot{E}_d \quad (29)$$

With:

$$e_1 = \left[(C_p)_a + \omega_1 (C_p)_v\right](T_1 - T_0) - T_0\left\{\left[(C_p)_a + \omega_1 (C_p)_v\right]\ln\left(\frac{T_1}{T_0}\right) - (R_a + \omega_1 R_v)\ln\left(\frac{P_1}{P_0}\right)\right\} + \mathrm{T}_0\left\{(R_a + \omega_1 R_v)\ln\left(\frac{1+1.6078\omega^0}{1+1.6078\omega_1}\right) + 1.6078\omega_1 R_a \ln\left(\frac{\omega_1}{\omega^0}\right)\right\} \quad (30)$$

$$e_3 = \left[(C_p)_a + \omega_3 (C_p)_v\right](T_3 - T_0) - T_0\left\{\left[(C_p)_a + \omega_3 (C_p)_v\right]\ln\left(\frac{T_3}{T_0}\right) - (R_a + \omega_3 R_v)\ln\left(\frac{P_3}{P_0}\right)\right\} + \mathrm{T}_0\left\{(R_a + \omega_3 R_v)\ln\left(\frac{1+1.6078\omega^0}{1+1.6078\omega_3}\right) + 1.6078\omega_3 R_a \ln\left(\frac{\omega_3}{\omega^0}\right)\right\} \quad (31)$$

Also we have:

$$e_p = \left[h_p(T,P) - h_p(T_0,P_0)\right] - T_0\left[s_p(T,P) - s_p(T_0,P_0)\right] \quad (32)$$

$$e_w = \left[h_f(T) - h_g(T_0)\right] + v_f\left[P - P_g(T)\right] - T_0\left[s_f(T) - s_g(T_0)\right] + T_0 R_v \ln\left[\frac{P_g(T_0)}{x_v^0 P_0}\right] \quad (33)$$

$$\dot{E}_q = \dot{m}_a e_q = \dot{m}_a\left(1 - \frac{T_0}{T_{av}}\right) q_1 = \left(1 - \frac{T_0}{T_{av}}\right) Q_1 \quad (34)$$

On the other hand, the exergy efficiency is presented as:

η_{ex} = Exergy for evaporation of moisture in product / Exergy of drying air supplied

Or mathematically:

$$\eta_{ex} = \frac{(\dot{m}_w)_{ev}\left[(e_w)_3 - (e_w)_2\right]}{\dot{m}_a e_1} \quad (35)$$

Where:

$$(\dot{m}_w)_{ev} = (\dot{m}_w)_2 - (\dot{m}_w)_4 \quad (36)$$

$$(e_w)_3 = [h(T_3, P_{v3}) - h_g(T_0)] - T_0[s(T_3, P_{v3}) - s_g(T_0)] + T_0 R_v \ln\left[\frac{P_g(T_0)}{x_v^0 P_0}\right] \quad (37)$$

$$P_{v3} = (x_v)_3 P_3 \quad (38)$$

Some works have shown the variation of the exergy inside a drying chamber during drying time, as illustrated in Figure 14 and Figure 15.

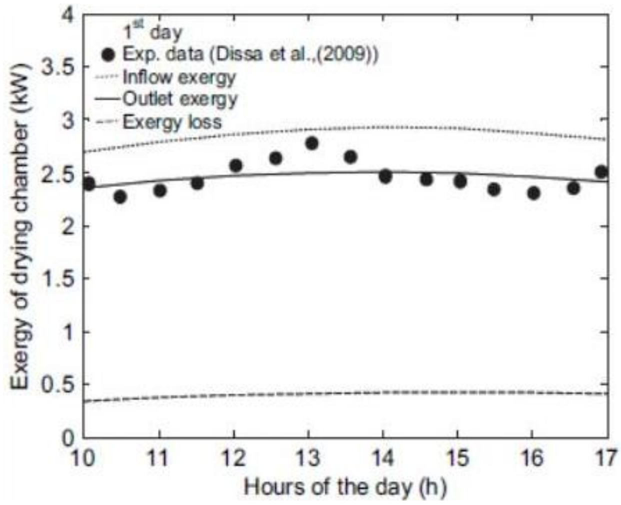


Figure 14. Variation of the drying chamber exergy as a function of the drying time[59]

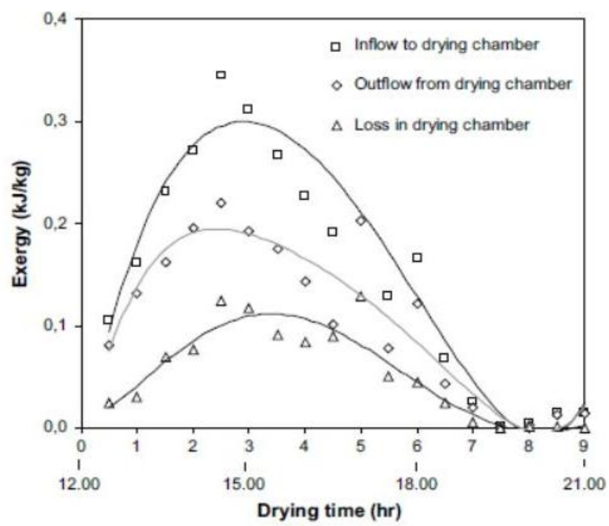


Figure 15. Variation of different exergy parameters inside the drying chamber[58]

This mathematical approach can be used to study thin or packed bed drying with a media supposed as porous[56, 62].

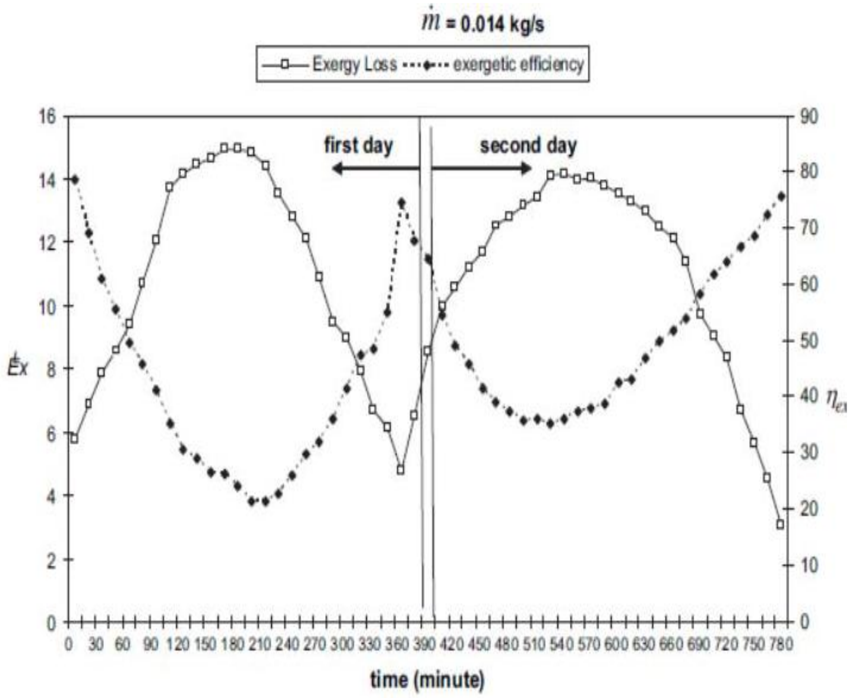


Figure 16. Variation of total exergy loss and total exergetic efficiency of a solar dryer[63]

3.3. Calculation of the System Exergy Efficiency

It is determined by:

Exergetic efficiency = 1-Exergy loss/Exergy input (39)

Where exergy loss and exergy input can be easily calculated using similar equations to equation 25 and equation 26 with adaptation to the solar drying system.

It is important to mention that in some specific cases for transparent walls of a solar dryer, there are radiations received by both the drying chamber and the solar collector then if the surface of the dryer is equal to the surface of the collector; the total exergy of radiation received by the system is double of the quantity presented by equation 27[49].

Total energy loss and exergetic efficiency of a solar dryer are presented in Figure 16.

5. Conclusions

Simulation and mathematical modelling plays an important role for the design of a solar drying system. To have an idea about the general behaviour of a solar drying system and to be able to calculate its energetic efficiency; it is important to establish heat and mass balance. This method is then applied for the different components of the drying system, which means both the solar collector and the drying chamber. It allows following the variation, in time and space, of different temperatures and parameters in particular temperature and humidity of the dried product and the heated air, necessary for the calculation of the energetic efficiency. For thick layers drying, the drying chamber is considered as a porous media and then mathematical treatment by using transfers in porous media can be done. Also, this method gives the variations of the air and product temperatures and humidity, permitting the calculation of the energetic efficiency for this case, too.

A detailed mathematical procedure to be adopted for calculation of the exergetic efficiency is proposed with application to a solar collector, to the drying chamber and the overall solar drying system. This mathematical procedure can be applied for both thin and thick layers. Exergetic efficiency can then be easily calculated by knowing some accessible parameters such as temperatures and humidity.

By means of the presented results, it is clear that the calculated efficiencies are deeply influenced by several parameters such as the variation of the received radiation, the external temperature and the wind velocity during drying time, by internal parameters and the design such as the surface of the solar collector, by the characteristics of the dried product. So, an optimum exploitation of the studied system with a minimum of expenses passes through simulating and modelling, in particular with calculation of energetic and exergetic efficiencies.

Nomenclature

Cp→specific heat (J/kg.K)
$\dot{m}$→mass flow rate (kg/s)
T→temperature (K)
t→time (s)

Section 2

A→surface of the collector (m^2)
F_R→heat removal factor of solar collector
F'→collector efficiency factor
h→coefficient of heat transfer by convection ($W/m^2.K$)
hr→adapted radiative exchange coefficient ($W/m^2.K$)

I, I_t→Incident radiation (W/m^2)
k→adapted conductive exchange coefficient (W/m^2.K)
LCV→lower calorific value of fuel (J/kg)
L→latent heat of vaporization of water (J/kg)
m→mass (kg)
m_b→mass of fuel consumed (kg)
P_f→energy consumption of fan/blower (J)
Q_u→useful energy gain of collector (W/m^2)
q→energy term (W/m^2)
surf→surface (m^2)
S→surface of wall dryer (m^2)
U_L→global heat loss coefficient (W/(m^2.K)
V→volumetric air flow (m^3/s)
W→weight of water evaporated from the product (kg)
*→precedent tray

Subscripts
ach→heated air
A→absorber
am→ambient air
b→brick wall
c→collector
fld→fluid (air)
f→product
I→insulator
int→interior side
i→input
i –l→Indices (reference table 1 or table 2)
o→output
p→insulator
pe→exterior face of the insulator
pi→interior face of the insulator
th→theoretical

Greek symbols
α→absorption coefficient
η→energetic efficiency
ρ→density (kg/m^3)
τ→transmission coefficient

Section 2.2
A→surface of contact air-product (m^2)
C→moisture content of the product (kg/kg)
D→coefficient of diffusion (m^2/s)
H→latent heat of vaporization of water (J/kg)
V→velocity (m/s)
w→humidity ratio (kg/kg)
y→coordinate (m)

Subscripts
eff→effective
f→fluid
s→solid (dried product)

Greek symbols
ε→bed porosity
σ→mass transfer factor (kg/m^{3}s)

Section 3
A_i→inlet area (m^2)
E_i→emissive power at inlet (W/m^2)
Ex→exergy (J)
$\dot{E}$→rate of energy flow
e→specific exergy
F_i→inlet shape factor
g→Gravitational acceleration (m/s^2)
h→specific enthalpy
J→Joule constant
m_a→mass flow rate of air (kg/s)
N_c→number of species
P→pressure (Pa)
Q→rate of heat transfer
R→Gas constant
s→specific entropy (j/kg.K)
u→specific internal energy (J/s)
v→specific volume (m^3/kg)
V→velocity (m/s)
x_v→mole fraction of vapor
z→altitude coordinate (m)

Subscripts
a→air
c→collector
d→destruction
exvrelated to exergy
g→saturated vapour state
i→inlet
l→loss
o→outlet
p→product
q→heat transfer related
v→vapor
w→water
∞→ambient
0→dead state

Greek symbols
μ→chemical potential (J/kg)
ω→humidity ratio of air
ω^0→humidity ratio of air at dead state

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