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Energy and exergy analyses of OMW solar drying process

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ABSTRACT

The energy and exergy analyses of the drying process of olive mill wastewater (OMW) using an indirect type natural convection solar dryer are presented. Olive mill wastewater gets sufficiently dried at temperatures between 34 °C and 52 °C. During the experimental process, air relative humidity did not exceed 58%, and solar radiation ranged from 227 W/m^2 to 825 W/m^2. Drying air mass flow was maintained within the interval 0.036–0.042 kg/s. Under these experimental conditions, 2 days were needed to reduce the moisture content to approximately one-third of the original value, in particular from 3.153 $g_{water}/g_{dry\ matter}$ down to 1.000 $g_{water}/g_{dry\ matter}$.

Using the first law of thermodynamics, energy analysis was carried out to estimate the amounts of energy gained from solar air heater and the ratio of energy utilization of the drying chamber. Also, applying the second law, exergy analysis was developed to determine the type and magnitude of exergy losses during the solar drying process. It was found that exergy losses took place mainly during the second day, when the available energy was less used. The exergy losses varied from 0 kJ/kg to 0.125 kJ/kg for the first day, and between 0 kJ/kg and 0.168 kJ/kg for the second. The exergetic efficiencies of the drying chamber decreased as inlet temperature was increased, provided that exergy losses became more significant. In particular, they ranged from 53.24% to 100% during the first day, and from 34.40% to 100% during the second.

1. Introduction

Thermal drying of wet materials is a basic operation in numerous industrial processes, and is characterised by a high energy intensity. Energy consumption always depends on the type of product to be dried, as well as on the technology used in the process. In general, the faster the drying speed, the greater the energy consumption, ASHRAE Handbook [1].

Thermal drying in solids might be regarded as the result of two simultaneous actions: a heat transfer process by which the moisture content of the solid is reduced, and a mass transfer process that implies fluid displacement within the structure of the solid towards its surface. Such motion is reported to depend on the structure, the moisture content and some other specific features of the material. Also, the separation of vapour from the solid substrate depends on the external pressure and temperature, on the total area of the solid surface, on Reynolds number and on the moisture content of drying air. Provided that thermal drying takes place very slowly at ambient conditions, drying plants are devoted to accelerate the process in order to achieve appropriate drying rates or, in other words, to supply the product with more heat than is available under ambient conditions [2]. Drying operations can be conducted with a renewable energy such as solar energy. Thermal energy is usually supplied either by preheating the air stream in contact with the sample product or by direct exposure to solar radiation (or also by both actions simultaneously). The drying air flow can be obtained by natural or forced convection. Ekechukwa and Norton [3] reported a detailed analysis of a large number of active and passive solar drying plants, focusing on their viability in rural areas.

One of the main goals in the design and optimisation of industrial drying processes is to use as less energy as possible for maximum moisture removal for the desired final conditions of the product. As a consequence, energy quantity and quality as well as heat and mass transfer should be investigated throughout the drying process [4]. Therefore, a rigorous analysis of the convective drying process should be based on the mass and energy conservation principles as well as on the exergetic balance of the process, i.e. on the first and second laws of thermodynamics.

The exergy of a thermodynamic system is defined as the maximum theoretical useful work (shaft work or electrical work) that can be obtained until thermodynamic equilibrium with the environment is reached, in presence of no other interacting system [5]. In order to achieve an efficient use of energy resources, exergy losses should be reduced as much as possible in

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Nomenclature

E	exergy (kJ/kg)
$\dot{E}$	exergy rate (kJ/s)
EUR	energy utilization ratio (%)
g	gravitational acceleration (m/s^2)
h	enthalpy (kJ/kg)
$\dot{Q}$	net heat rate (kJ/s)
$\dot{W}$	energy utilization rate (kJ/s)
S	entropy (kJ/kg K)
U	internal energy (kJ)
P	atmospheric pressure (kPa)
p	pressure (kPa)
m	mass (kg)
$\dot{m}$	mass flow rate (kg/s)
$\bar{c}_p$	mean specific heat (kJ/kg K)
t	drying time (h)
T	temperature (K)
V	volume (m^3)
v	velocity (m/s)
u	specific volume (m^3/kg)
w	specific humidity (g/g)
z	altitude coordinate (m)

Greek symbols

ϕ	relative humidity (%)
ε	exergetic efficiency (%)

Subscripts

amb	ambient conditions
h	heater
i	inlet, inflow
o	outlet, outflow
0	surrounding or ambient
da	drying air
dc	drying chamber
L	loss
mp	moisture of product
sat	saturated
sys	system
uda	useful energy gain by the drying air
wp	moisture removed from product

all physical processes. In this sense, one of the main goals of exergetic analysis is to locate and characterise the causes of exergy destruction or exergy loss, as well as to quantify the corresponding rates.

Numerous research works relating the mathematical modelling and the kinetics of the drying process of vegetables, fruits and agrobased products are available at present in the scientific literature, such as those concerning pistachio [6], green beans [7], okra [8], carrots [9], bananas [10], potatoes and apples [11], red peppers [12], figs [13], mint leaves [14], eggplants [15], green peas [16], black tea [17] and prunes [18]. Some other works are focused on the industrial agrobased wastes, like olive cake [19–21] and sludge from olive oil extraction [22,23]. However, only a few research works including simultaneous energy and exergy analyses of the drying process are available [24,25,4,26].

Olive mill wastewater (OMW) comes from the vegetable water of fruit and the fresh water used in the production process of olive oil extraction plants, and contains olive pulp, mucilage, pectin, residual oil, different dissolved mineral salts, etc. OMW's typical weight composition is [27] 83–96% water, 3.5–15% organics and 0.5–2% mineral salts. The organic fraction consists of sugars (1.0–8.0%), N-compounds (0.5–2.4%), organic acids (0.5–1.5%), fats (0.02–1%) as well as phenols and pectins (1.0–1.5%).

No information about the energy and exergy analyses of OMW's solar drying process is available in the scientific literature. Provided the high solar radiation levels in the southern regions of Europe, and in particular in the Mediterranean area (where most of the olive oil extraction plants are located), we regard works on the design and construction of solar drying plants which lead to an improvement of OMW's environmental management as having great interest. Note, for instance, that the total amount of olive processed in Spain reaches an approximate value of 5.5×10^6 ton [28] which generate around 4×10^6 ton/year sludge and OMW. This gives a hint of the magnitude of the environmental problem caused by olive oil industry in that country.

The present work is intended to provide a possible solution to the above-mentioned problem. To do so, a laboratory-scaled prototype solar drying plant has been designed, and a series of experiments have been carried out in order to achieve relevant data on the energy and exergy analyses of OMW's solar drying process.

2. Material and methods

2.1. Material

The samples of fresh OMW were obtained from a cogeneration plant for the treatment of the sludge generated in the olive oil extraction plant "Troil Vegas Altas SC", located in the surroundings of Guareña (Badajoz) in southwestern Spain, in April 2006. The OMW used in the experiments showed an initial content of moisture $(75.9 \pm 0.5)\%$ by weight (wet basis), which was determined by drying it in an oven at 105 °C for 4 h and performing the operation in triplicate in order to obtain a reasonable average.

2.2. Experimental setup

The experimental setup, shown in Fig. 1, consisted of a solar air collector, a drying chamber, an optional operating circulation fan, a chimney and the base structure. The air heater was simple type, with upper air flow device and external dimensions $1000 \times 1000 \times 94$ mm. It had a 1 mm thick absorber black aluminium plate, covered by a 3 mm transparent methacrylate plate and

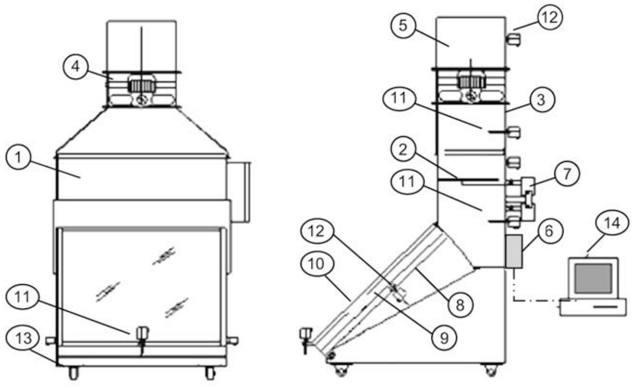

Fig. 1. Experimental setup. (1) Drying chamber. (2) Tray. (3) Load door. (4) Fan. (5) Chimney. (6) Control panel and data transmission. (7) Load cell. (8) Polystyrene plate. (9) Black aluminium plate. (10) Cover. (11) Temperature and relative humidity sensors. (12) Flux controlling sensor. (13) Support wheel. (14) Computer.