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Experimental study of the thermophysical properties and drying kinetics of Moroccan anchovy by convective solar energy in thin layers

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Abstract

The purpose of this work was to study the effect of the air-drying process on the dehydration kinetics of anchovy fillets. Experimental drying kinetics was measured at four air temperatures (50, 60, 70 and 80 ° C), a constant relative humidity of 150 m^3 / h. The drying kinetics of the anchovies was accelerated by increasing the air temperature and was displayed. During the study of the drying operation and storage conditions, it is necessary to know the relationship between the content in equilibrium moisture (X_e) material and water activity (a_w). The moisture desorption isotherms of the anchovy filings were determined at three temperatures (30, 40 and 50 ° C) using the static gravimetric method to determine the optimum amount of water activity for the conservation of the fillets anchovy.

1. Introduction

Fish is, by definition, a major source of high quality protein for humans [1]. Fish is a highly perishable food product with a very short life span because of the large amount of water it contains 80% [2] which produces reactions and micro-organisms can generate enormous environmental impacts.

The anchovies of the family Engraulidae are grouped into seven species of small pelagic fish that meet in the Mediterranean Sea, the Atlantic Ocean, the Pacific Ocean and the Indian Ocean [3]. Anchovies are eaten fresh, frozen, salted, canned, marinated or in the form of anchovy paste. The volumes of anchovy caught have fluctuated considerably over the last 60 years, from 540 000 tonnes in 1950 to 14.5 million tonnes in 1970, to fall to 2 to 7 million tonnes over the next 20 years [4]. During the current decade, catches have stabilized around an average of 12.5 million tonnes per year during the period 1999-2005 [5].

Many aquatic and marine products consumed in Morocco in large quantities are not always available depending on the season. Several solutions have been proposed to overcome this shortage: smoking, freezing and preserved by drying. Solar drying is a simple, safe and adequate solution for a wide range of seafood products.

The drying of food in the sun has been a known process for centuries, and the methods used have hardly changed. The products are often badly dried and invaded by parasites. The use of more satisfactory sun drying techniques and the introduction of solar dryers [6]. Drying requires energy and heat depending on the moisture content of the air, the drying system used, the drying temperature and the specificities of the product concerned (thickness, area, and air resistance).) and the moisture contained in the element to be dried. The operation of the dryer will depend directly on the amount of irradiation and the humidity of the place of use [7]. There are two main types of solar dryers: direct solar dryers and indirect solar dryers. in our work we use the 2nd types of dryers.

This work aims to:

- Reduce energy and environmental costs by using solar energy.
- Evaluate the diffusion coefficient and activation energy of the product.
- Determine the desorption isotherms of sardine fillets at 30, 40, and 50 ° C and then to evaluate the optimal conservation activity, an indispensable value and acting as the identity of a product during its handling.
- Determination of drying kinetics of Anchovy under various aero-thermal conditions in order to define its thermal identity.

2. Material and Methods

2.1. Sorption Isotherms

Fresh anchovies were obtained from the regional Marrakech-Asfi fish market, frozen and introduced into the laboratory. The mass and size of the anchovies were 10 g, 4 cm, 2 cm and 1.5 cm in length, width and thickness, respectively.

For the determination of desorption isotherms of anchovies from Essaouira, we opted for the static gravimetric method. This method ensures the regularization of moisture by contact with aqueous salt solutions above which the vapor pressure of the water at a given temperature is perfectly known. The saturated saline solutions used are: KOH, ($MgCl_2$, $6H_2O$), K_2CO_3, $NaNO_3$, KCl and ($BaCl_2$, $2H_2O$). These solutions make it possible to obtain relative humidity ranging from 5 to 90% [8].

Saturated salt solutions and their corresponding water activities at different temperatures are given in Table 1:

Table 1 : Saturated salt solutions and their corresponding water activities at different temperatures

	KOH	$MgCl_2$, $6H_2O$	K_2CO_3	$NaNO_3$	KCl	$BaCl_2$, $2H_2O$
30°C	0.7380	0.3238	0.4317	0.7275	0.8362	0.8980
40°C	0.6260	0.3159	0.4230	0.7100	0.8232	0.8910
50°C	0.5720	0.3054	0.4091	0.6904	0.8120	0.8823

Figure 1 illustrates the experimental setup used. It consists of an oven filled with six jars each containing a different saline solution figure 1. Each sample is put in a small bottle and placed on a tripod placed in each jar. The jars must be tightly closed so that the partial pressure of the water vapor remains constant throughout the experiment. In jars where the air humidity is high (saturated solutions of salts NaNO3, KCl and BaCl2), the flasks are provided with a protective cover against the droplets which come from the condensation in order to avoid the rewetting of samples [9].

The desorption experiments carried out were carried out at three different temperatures: 30, 40 and 50 ° C and at six values of the relative humidity.

The samples are weighed every two days until the mass change between two successive measurements becomes about 1%. The thermodynamic equilibrium is then considered to be reached. As soon as the equilibrium wet masses are determined, the samples are introduced into an oven at 105 ° C for 24 hours to determine their dry masses [10].

Figure 1 : Experimental device for the measurement of sorption isotherms.

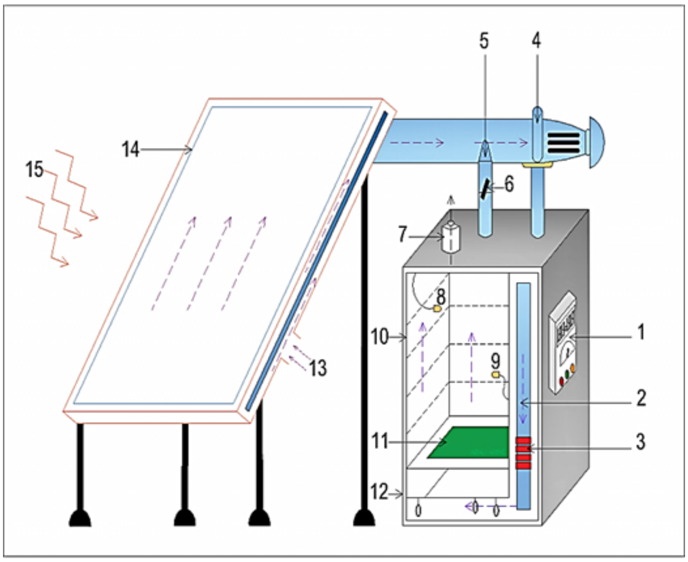
After obtaining the wet and dry masses of all samples, the equilibrium water contents are calculated using the following relationship:

$$X_{eq} = \frac{m_h - m_s}{m_s} \qquad (1)$$

Withe: m_h and m_s are the mass before and after drying, respectively.

2.2. Drying Kinetics

Drying involves decreasing the water activity of the dried products to a value ensuring their preservation. The process must meet certain quality criteria related to the product while ensuring a reasonable pace and cost for the production line. The studied system is an indirect convective dryer coupled to a solar collector operating in forced convection (figure 2). It is a system without storage with total or partial recycling of air [11].



(1)control box, (2) suction duct , (3) electrical back-up, (4) fan, (5) ventilation duct, (6) air flap, (7) air outlet , (8) humidity sensor, (9) thermocouple , (10) floors, (11)sample holder, (12) drying cabinet, (13) air inlet, (14) solar collector, (15) Sun rays.

Figure 2: Convective solar dryer installed in Marrakech.

In order to ensure a better stability of the drying conditions and a homogenization of the temperature inside the dryer, all the apparatus must operate at least half an hour before the introduction of the trays loaded in the chamber of drying. The weighing of the trays is carried out outside the dryer. The interval of the weighing time of the trays is of 10 min at the beginning of the experiment and reaches 60 min at the end. The weighing time is of the order of 60 to 90 s and is deducted from the total drying time of the product. The measurement at time t gives us the wet mass of product. The drying experiment is stopped when three successive measurements of the mass of the rack show a difference not exceeding 0.01 g. The temperature measurement at the entrance to the drying chamber is carried out using a precision thermoregulatory ± 1.5 ° C connected to a platinum probe. The relative air humidity at the entrance to the drying chamber is measured using a ± 2% Humicolor digital display probe. The wet masses of the product are carried out by means of a digital electronic balance with an accuracy of ± 0.001 g. This method of measurement makes it possible to follow the decrease in the weight of the product during drying. In order to determine the dry mass of the product, the samples dried in the wind tunnel are then placed in an oven regulated at 105 ° C. for 6 to 7 hours. The product is weighed every hour until it reaches maximum dehydration. The moisture content of the drying sample at time t can be converted to reduced water content X* by:

$$X^* = \frac{X(t) - X_{eq}}{X_0 - X_{eq}} \quad (2)$$

With:

X(t): The water content at each instant (g water / g d.b).

X_{eq}: the water content of equilibrium (g water / g d.d).

X_0: the water content at the initial time (g water / g d.b).

The water content at equilibrium corresponds to the limit value obtained after an infinite time for a product subjected to given conditions of temperature and hygrometry.

The drying speed $\left(-\frac{dX}{dt}\right)$ is normalized or reduced by the speed of the first phase $\left(-\frac{dX}{dt}\right)_0$ is which either can be deduced theoretically or measured on the experimental curve. This allows you to write:

$$f(x) = \frac{-\frac{dX}{dt}}{\left(-\frac{dX}{dt}\right)_{t_0}} \quad (3)$$

The modeling of the drying curves consists of defining a function satisfying the equation: $X^* = f(t)$ which is called the drying characteristic equation. Table 2 summarizes the characteristic drying equations found in the literature to describe the solar drying kinetics of a product.

3. Results and discussion

3.1. Desorption isotherm

The hygroscopic balance of anchovies is reached after eight days for desorption.

The experimental isotherms of water desorption at 30, 40 and 50 ° C are presented in Figure 3. They have a sigmoidal shape (isothermal type II). These figures show that for a water activity aw of constant medium, the equilibrium water content X inversely increases with temperature. This phenomenon can be explained by the fact that for high temperatures, the state of excitation of the molecules is higher; this is due to the decrease of the attractive forces of water molecules between them.

Table 2: Models applied to the description of drying curves of anchovy.

Model name	Equation	References
Newton	$X^* = \exp(-kt)$	[12]
Page	$X^* = \exp(-kt^n)$	[13]
Henderson and Pabis	$X^* = a.\exp(-kt)$	[14]
Logarithmic	$X^* = a.\exp(-kt) + c$	[15]
Two-term	$X^* = a.\exp(-k_0 t) + b.\exp(-k_1 t)$	[15]
Two-term exponential	$X^* = a.\exp(-kt) + (1-a)\exp(-kat)$	[16]
Wang and Singh	$X^* = 1 + at + bt^2$	[17]
Diffusion Approach	$X^* = a.\exp(-kt) + (1-a)\exp(-kbt)$	[18]
Midilli-kucuk	$X^* = a..\exp(-kt^n) + bt$	[19]

In addition, for constant temperatures, equilibrium water content X_{eq} increases with increasing water activity. They have a sigmoidal shape (isothermal type II). This is in agreement with the behaviour of other agri-food products [20–22].

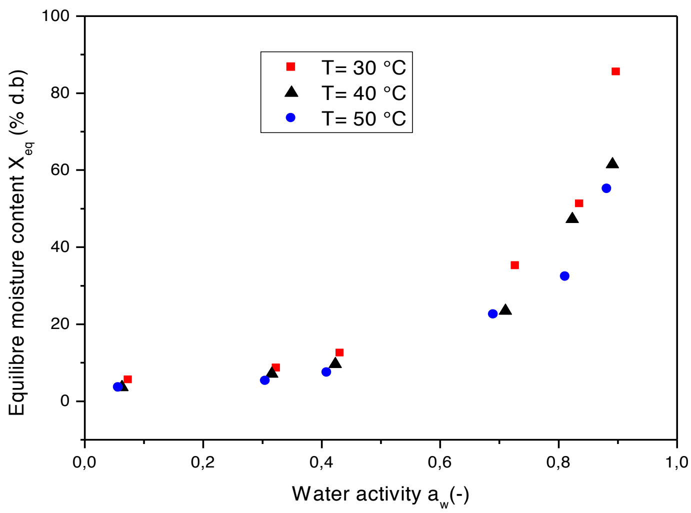


Figure 3: Desorption isotherms of Anchovy.

3.2. Optimal conditions for storage

All agri-food products must undergo quality treatment. processes must provide users with accurate information on how to manage a product during handling, storage and storage [23]. To this end, we have determined the optimal water balance activity for anchovy conservation. Indeed, the sorption isotherm can be modeled in particular under a 3rd degree function. The central part or "plate" corresponds to the zone of better stability of the products. This makes it possible to calculate the value for which the second derivative is canceled (no inflection) and consequently the optimal relative humidity of conservation. The value of the optimal water activity for conservation of anchovy is $a_w = 0.33$ it belongs to the interval $[0.2 - 0.4]$ [24].

Polynomial equation of the optimal water activity for conservation of anchovy as:

$$X_{eq} = -1.93245 + 111.80092a_w - 360.18134a_w^2 + 360.04623a_w^3 \quad (4)$$

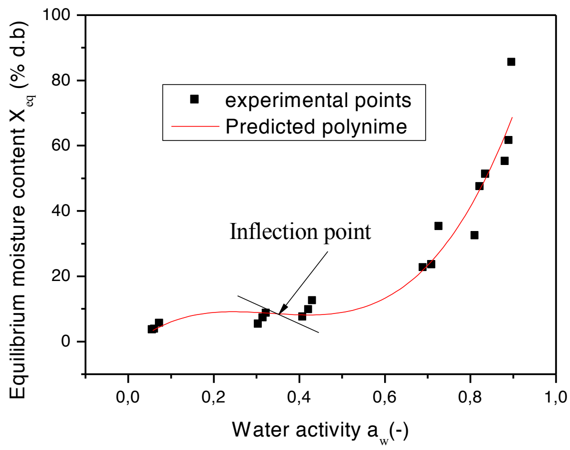


Figure 4: Optimal water activity for conservation of Anchovy.

3.3. Drying Kinetic

The variation of moisture content and the drying rate versus drying time at different drying conditions are given in Figure. 5 and 6 respectively. Figure 5 shows the evolution of the water content as a function of time for different temperature conditions. The evolution of the drying rate as a function of the water content is shown in Figure 5.

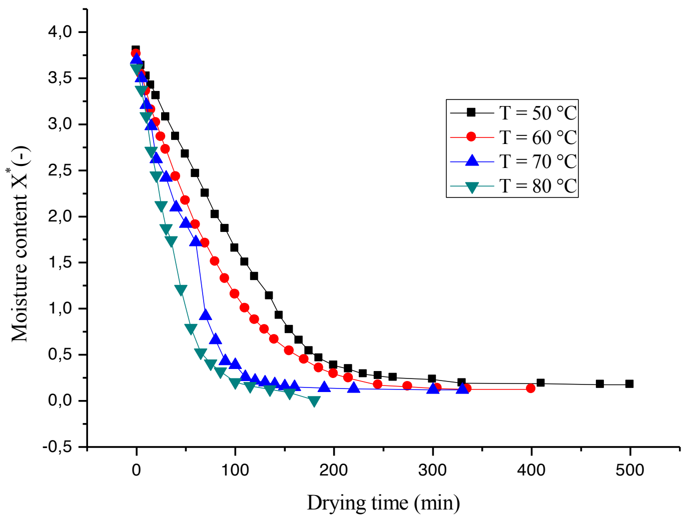


Figure 5: Evolution of the moisture content of anchovy versus the drying time.

The reduced water content decreases as the set temperature increases. The drying time of the anchovies was significantly reduced from 500 to 180 min. The variation of drying rate versus moisture content for multiple drying conditions anchovy is shown in Fig. 6. The variations in the drying speed as a function of the anchovy drying time are given in figure 7. It will be noted that the drying speed continuously decreases with the decrease in the drying time. The drying rate increases with increasing temperature of the drying air and the highest drying speed values were found in the experiment for 50 ° C.

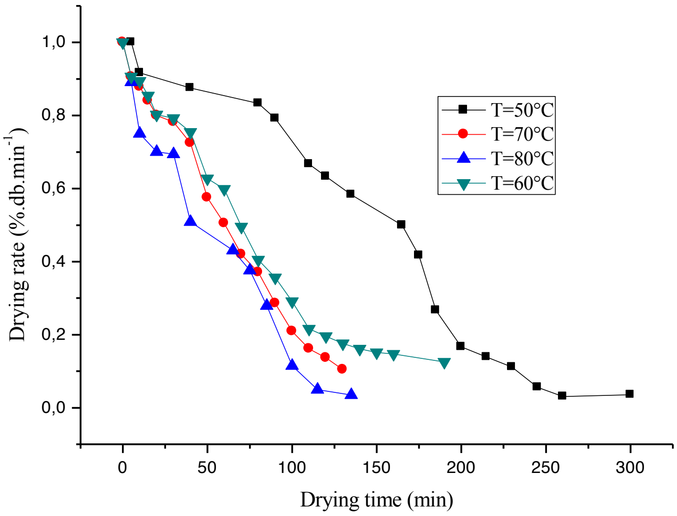


Figure. 6: Influence of drying air temperature on drying rate during drying of Anchovy.

3.4. Smoothing drying curves of anchovies

The appropriate model for describing the shape of the drying kinetics of anchovy is chosen according to the following criteria:

• High correlation coefficient (R^2)

• Minimum systematic error (S)

• Chi-square minimal reduced.

The Logarithmic model seems to better describe the drying kinetics of anchovy because it has the highest value of R^2 and the lowest values of $\chi 2$ and S.

3.5. Effective moisture diffusivity

Diffusion is generally considered to be the primary mechanism for transporting moisture to the surface to be evaporated. The effective diffusivity of humidity can be determined from the slope of ln (X *) as a function of time. The experimental results can be treated by the Fick diffusion equation. The analytical solution of Fick's second law, using the following equation:

$$\ln\left(X^*\right) = \ln\left(\frac{8}{\pi^2}\right) - \left(\frac{\pi^2 D_{eff}}{4L^2}\right) \times t \quad (5)$$

With:

D_{eff}: The coefficient of effective diffusivity (m^2/s)

L: The half-thickness of the product (m).

The effective diffusivity varies from 1.92 10^{-9} to 6.19.10^{-9} m^2 / s for a flow rate of 150 m^3 / h with the increase in temperature (Table 3).

These D_{eff} values are within the general range 10^{-11} m^2 / s <D^{eff}<10^{-9} m^2 / s for food products.

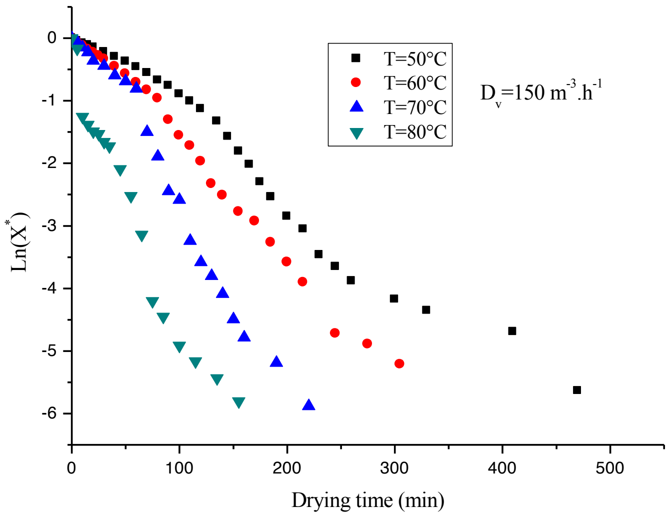


Figure 7. Ln (X *) as a function of drying time.

Table 3: D_{eff} values for the four temperatures:

T (°C)	50	60	70	80
D_{eff} (m^2/s)	$1.92.10^{-9}$	$2.72.10^{-9}$	$4,40.10^{-9}$	$6.19.10^{-9}$

The diffusion coefficient increases as the temperature increases.

The activation energy is calculated by representing the natural logarithm of the experimental values of the effective diffusivity D_{eff} as a function of the inverse of the temperature, therefore Equation (III.11) is transformed into the form:

$$\ln\left(D_{eff}\right)=\ln\left(D_0\right)-\frac{E_a}{R}\left(\frac{1}{T}\right) \quad (6)$$

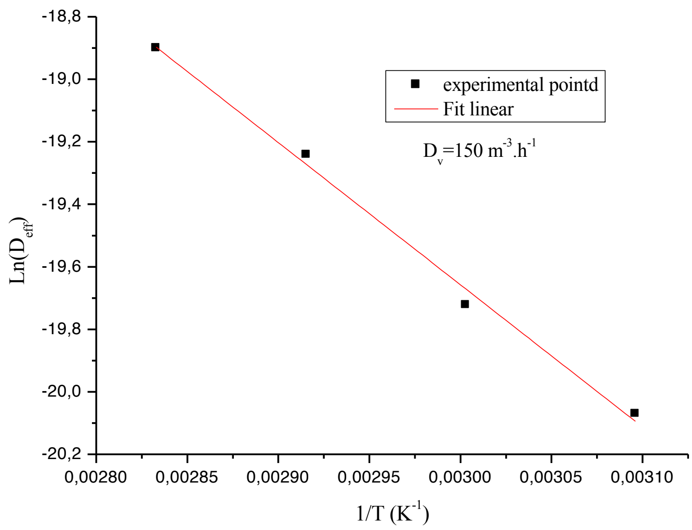


Figure 8: Influence of the drying temperature on the effective diffusion coefficient.

The value of E_a found from this study is 14.67 kJ / mol. The obtained value agreed those obtained in previous works [25].

Conclusion

The drying experiments are carried out at different temperatures (50, 60, 70 and 80 ° C) and at a flow rate of 150 m^3 / h. The results show that the drying time decreases with increasing temperature.
The main factor that influences the drying kinetics of anchovies is the temperature of the drying air.
The effective diffusion coefficient, which groups together the different transport phenomena, is determined according to a law similar to Fick's second law (Madamba's approximation). The simultaneous effects of temperature and drying air flow on the effective diffusivity D_{eff} are mentioned. We notice an increase in D_{eff} with temperature and with hot air flow. Activation energy, which represents the energy barrier the system must cross to stabilize, is determined for anchovies using the Arrhenius equation.

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