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Experimental Study of Drying Kinetics of Sage in a Drying Tunnel Working in Forced Convection

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Abstract — *Sage (salvia officinalis) is among the most consumed aromatic herbs in Morocco. The present work examines the effect of drying conditions (drying air velocity, drying air temperature and air moisture content) on drying kinetics of sage in a laboratory drying tunnel working under air controlled conditions. The results showed, that temperature is the main factor in controlling the product drying rate. The expression of the drying rate is determined empirically from the* ***characteristic curve of drying*** *(C.C.D). This kind of formula is necessary for programs simulating solar drying systems.*

Résumé — *La sauge (salvia officinalis) constitue l'une des tisanes les plus consommées au Maroc. Le présent travail étudie l'influence des conditions de séchage (la vitesse de l'air asséchant, la température de séchage et la teneur en eau du produit) sur la cinétique de séchage de la sauge dans une soufflerie à atmosphère contrôlée. Les résultats obtenus montrent que la température de séchage constitue le facteur principal influençant la vitesse de séchage du produit. L'expression de la vitesse de séchage de la sauge est déterminée à partir de la* ***courbe caractéristique de séchage*** *(C.C.S). Ce type de corrélation empirique est indispensable pour la simulation numérique des séchoirs solaires convectifs.*

Key words : Drying – Sage - Drying rate - Laboratory drying tunnel - Forced convection

1. INTRODUCTION

In drying literature, different models and theories are used in order to study drying kinetics and apprehend physical laws governing heat and mass transfer during the drying process [1]. However, since the transfer mechanisms are complex and the biological products are abundant, a unique model could not represent all the situations.

We note that experimenters [2,3] study drying kinetics of a given product so as to determine empirically its drying rate. The empirical relations obtained are usually used in models and programs simulating the behavior of a thin-layer solar drier. The problem which is raised to different researchers, working on simulation of drying systems, is that they do not often have the expression of the product drying rate. Thus, in a previous work, Kouhila [4] used in his computational program the expression of apple drying rate in order to simulate the drying kinetics of apricot. Since apple and apricot have similar geometrical shapes, he supposed that apricot and apple have nearly the same drying kinetics because he didn't have the relation expressing the drying rate of apricot.

Thus, the main objective of the present work is to determine drying kinetics of one of the most consumed aromatic herb in Morocco, which is the sage. This kinetics is studied in a laboratory drying tunnel where the product is put in thick-layer under controlled air conditions. The undertaken experiments consist of studying the separated influence of drying air conditions (drying temperature, drying air velocity and air moisture content) on the drying rate. Using an empirical approach, we try to determine the *characteristic curve of drying* (C.C.D) and to elaborate the equation describing the drying rate of sage. These empirical formulas are useful for the simulation and modeling of solar and conventional drying systems and processes.

2. MATERIAL AND METHOD

2.1. Description of the Experimental Apparatus

The different experiments undertaken consist of studying the drying kinetics of sage in a drying tunnel working by forced convection under controlled atmosphere. The experimental apparatus is supplied with instruments measuring drying air velocity, temperature of drying and air moisture content [2,5].

The experimental apparatus (figure 1), is a laboratory drying tunnel, which provides an airflow with controlled characteristics. The air conditions could be varied from an experiment to another.

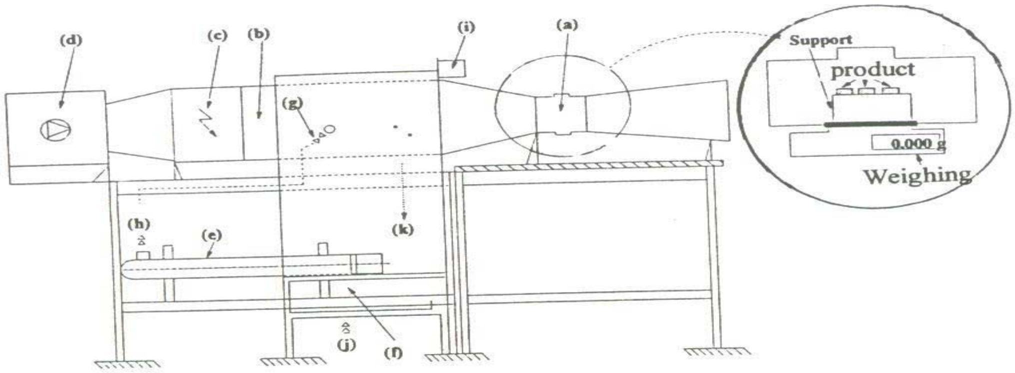

Figure 1: Schematic representation of the laboratory drying tunnel
(a) experimental chamber (b) humidifier (c) heating system (d) fan
(e) heating system (f) electrical water valve (g) water valve (h)hot water
(i) humidity and temperature probes (j) cold water (k) evacuation

The whole apparatus, held up on a frame, includes :

- An air treatment system (d) with a regulating fan velocity enabling us to have an average air velocity varying between 4 and 12 $m.s^{-1}$.. In order to have low air velocity that is necessary for drying processes, we have adopted the inlet air system. The airflow is, therefore, made uniform by means of a honeycomb device placed upstream the last system.
- A heating system (c) equipped with a 24 kW power supply and regulated by a temperature probe.
- A water humidifier (b) supplied, through a vaporizer (e), with variable temperature water The system is regulated by a humidity probe. It is characterized by :
    - a power supply: 12 kW ;
    - a water flow rate : 1.4×10^{-4} $m^3.s^{-1}$;
    - a maximum air moisture content : 80 %.

- An experimental chamber (a) of (25 cm x 25 cm) dimension equipped with a convergent so as to have a uniform velocity repartition. The sample is fixed inside this chamber and the thermocouples and Pitot tube are placed at its entrance.
- A control desk for :
  - the heating battery regulator ;
  - the air moisture regulator ;
  - the ventilation velocity ;
  - the electrical water gate of the humidifier circuit.

2.2. Measured parameters

The measurement method consists of fixing the values of the drying air velocity and the drying temperature for every test. The system is left for an hour until it reaches its equilibrium temperature. The product is introduced in the experimental chamber. From this moment on, we began to follow the variation of the weight of the product as a function of time. The time separating two successive measurements is about a few seconds in the beginning of the drying process. As the loss of mass of the product decreases during drying, the time interval between two successive measurements is increased until it reaches an hour at the end of drying [2]. The parameters measured during every experiment are :

- **The temperature:** it is measured by Chromel/Alumel thermocouples. The diameter of every thermocouple is d = 1 mm and the measurement accuracy is about 0.5 K. The different temperatures are measured :
  - at the surface of the product ;
  - in the drying air ;
  - in the inlet and outlet of the experimental chamber.
- **The air moisture content :** the air moisture content is measured by a thermal hygrometer with an accuracy of 0.1 %.
- **The drying air velocity :** the drying air velocity is measured by a digital velocity meter connected to a Pitot tube placed in the experimental chamber near the surface of the product. The measurement accuracy is 0.1 $m.s^{-1}$.
- **The mass of the product:** it is measured by a digital weighing apparatus with an accuracy of 0.001 g. This weighing apparatus enables us to determine continuously the 'loss of mass' of the product during the drying process.
- **The mass of the evaporated water :** There are different methods for measuring the product water content during drying process. These methods could be classified according to the contact mode between the drying air and the product and to the estimating method of determining the evaporated water quantity :
  - **a)** The measurement of the drying air moisture gap, before and after its passing through the drying product, is carried out continuously by infrared radiation. This method has the advantage of being independent of the drying cell, but necessitates an appreciable variation of the drying air moisture content [3, 5, 6].
  - **b)** The continuous measurement of the product mass dispersed in thin layer on the tray of the weighing apparatus was the object of several investigations [3, 5, 6]. The main difficulty, related to this method, resides in the fact that we measure also the air thrust exerted on the tray. This air thrust is proportional to the load loss due to the product layer set down on this tray and depends in addition on the

product geometrical shape. In the case of distorted products, this air thrust would be important and could involve significant variations.

So, the solution adopted by several experimenters consists of stopping the fan during the weighing time or, to avoid the air flux, by deviating it by means of a register game. In this case, we measure continuously the mass of the product. The perturbations, due to the flux interruptions and affecting the drying process, involve additional experimental errors in measurement.

It is the continuous weighing technique, which is used in this work despite the difficulty encountered at the level of the air thrust on the grilled cage. We checked experimentally, using several tests, that this air thrust remains approximately constant. The frontal surface opposite to the flux is, in our case, small and invariable during the drying process [5].

2.3. Experimental set-up

Since the sage leaves are considerably light and their dimensions are very small, the experiments could not be undertaken on isolated leaves. So, we were led to dry our aromatic herb in thick-layer [2]. The digital weighing apparatus enables us to measure the loss of mass of the product during the drying process. This weighing apparatus plays also the role of a stand for the product drying. Nevertheless, for the same reasons evoked above, a weak airflow rate pushes the product outside the vein. In order to remedy to this problem, we used a grilled cage as a support for the product. This grilled cage is placed upon the weighing apparatus.

2.4. Determination of the drying curves

The drying curves are the curves representing the variations of water content X as a function of time, or those representing the drying rate, $(-\frac{dX}{dt})$, versus X, or a dimensionless form of the last curves so as to give a unique representation at different drying conditions.

The experimental curve obtained is : X = f (t). It is the curve, which contains the most information.

The curve representing $f(X) = (-\frac{dX}{dt})$ could be plotted by calculating the derivative of X (t) directly from the experimental data points or after fitting the curve representing X as a function of time.

The drying curves are determined from the variation of the product water content X as a function of time. The product wet mass M_w is weighed during the drying process. The product dry mass M_d is then obtained by placing the dried product in an oven regulated at 105 °C until the product is completely dehydrated [1]. The dry mass M_d is necessary for the computation of X.

3. DRYING KINETICS OF SAGE

3.1. Experimental results

We study in this paragraph the variation of the product water content as a function of time and the influence of the drying air velocity and the drying air temperature on the drying rate in order to determine the *characteristic curve of drying*. Our experiments are undertaken at different air conditions (Table 1).

Table 1: Drying air conditions during experimentation

Experiment number	Drying air velocity V ($m.s^{-1}$)	Dry-bulb temperature T_a (°C)	Wet-bulb temperature T_h (°C)	Air moisture content h (%)
1	2.1	30	17.9	28
2	2.6	30	20.4	29.1
3	3.1	30	19.2	30
4	1.8	30	17.2	24.2
5	2.6	40	23.8	17.9
6	2.3	42.8	24.5	16.2
7	2.6	50	25.7	13

The curves represented in figures 2 and 3 at different air conditions illustrate the influence of aerothermal parameters on the drying rate.

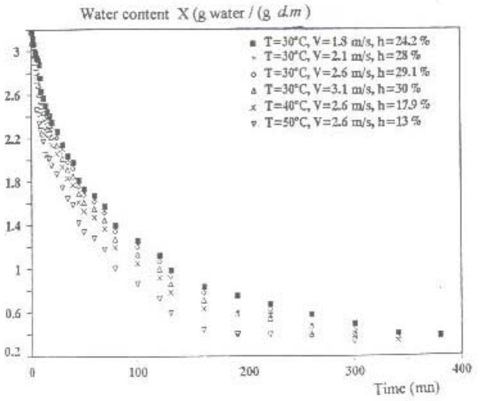

Fig.2: Variation of the product water content as a function of time for different drying air conditions

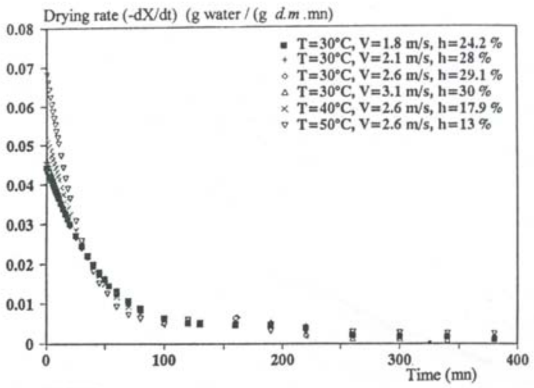

Fig.3: Variation of the drying rate as a function of time for different drying air conditions

3.2. Influence of aerothermal parameters

3.2.1. Influence of temperature

In order to study the influence of drying air temperature on drying kinetics of sage, we vary the air temperature from 30 °C to 50 °C at constant air velocity (V = 2.6 $m.s^{-1}$). Since it was not possible to fix air moisture content, its influence appears to be less important in comparison with drying air temperature especially at the falling rate period (phase 2).

Figures 4 and 5 represent respectively the variation of the sage water content as function of time and of the drying rate of sage as function of time for different drying air temperatures. These curves show that in our experimental air conditions, there is no constant rate period (phase 1) in the drying process of sage.

According to our experimental results, the temperature of drying seems to be the most important parameter influencing drying kinetics of sage. This result is confirmed by Van Arsdel et al. [7]. Drying kinetics depends greatly on temperature, especially for biological products presenting a big internal resistance to water migration. Variation of temperature within the product modifies water activity in it, but exerts an influence on other factors such as evaporation heat of liquid water, which varies as a function of temperature. In this case, the measurement of the product temperature during drying enables us to understand the modifications of drying kinetics or to take into account changes in product quality.

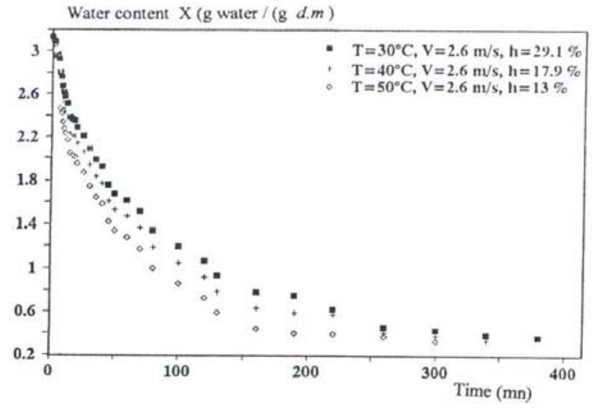

Fig. 4: Influence of the drying air temperature on the evolution of water content as a function of time

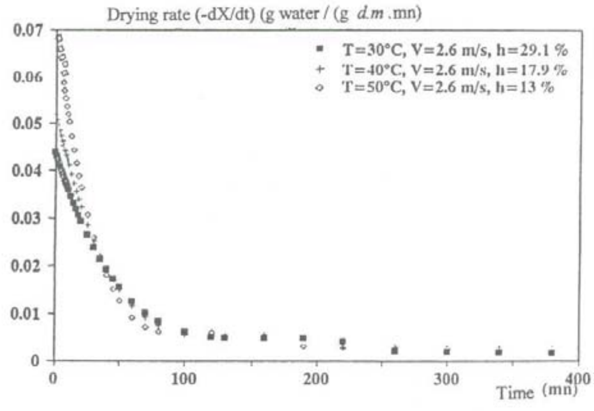

Fig. 5: Influence of the drying air temperature on the evolution of the drying rate as a function of time

Figure 6 shows the evolution of the temperature at the surface of the product as a function of duration time. We note that, for different cases, the temperature at the surface of the product increases gradually until reaching drying air temperature at the end of drying process.

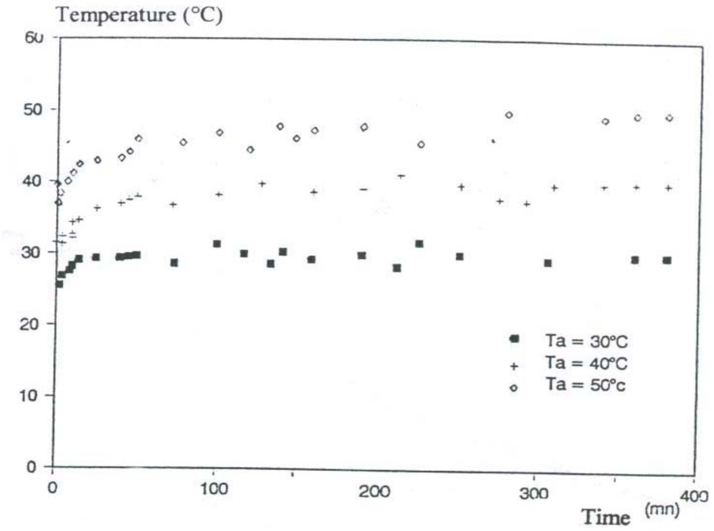

Fig. 6: Evolution of the temperature at the surface of the product as a function of time (V = 2.6 m.s^{-1})

3.2.2. Influence of drying air velocity

In order to study the effect of drying air velocity on drying kinetics of sage, we present the variation of the product water content and drying rate as a function of time (figures 7, 8, and 9) for four values of drying air average velocity (1.8 ; 2.1 ; 2.6 and 3.1 $m.s^{-1}$). In this velocity interval, the drying rate does not vary a lot as a function of drying air velocity. Daudin [8] worked on drying of maize, and came to the same conclusion. This fact corroborates our experimental results.

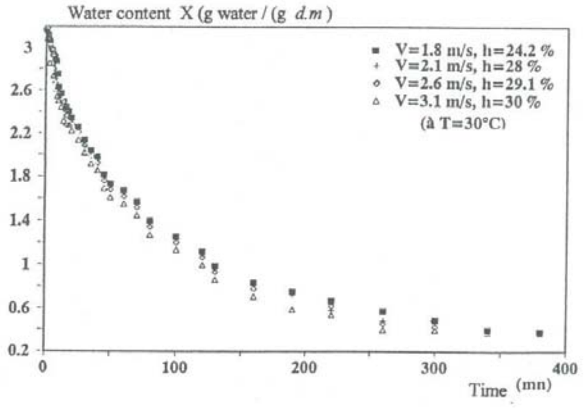

Fig.7: Influence of the drying air velocity on the evolution of water content as a function of time

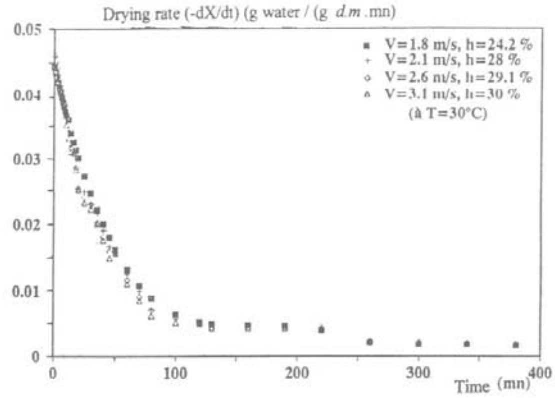

Fig.8: Influence of the drying air velocity on the evolution of drying rate as a function of time

Drying air velocity is a parameter, which intervenes essentially in heat and mass transfers taking place between the product and the air. It has a remarkable influence on the rate of drying when drying kinetics presents a constant rate period (phase 1). In return, when the product does not present a constant rate period, drying air velocity has a weak influence. This fact shows that heat and mass transfers by convection are not limitable factors in the drying process. They are internal factors, which control water transfer velocity from the interior towards the surface of product.

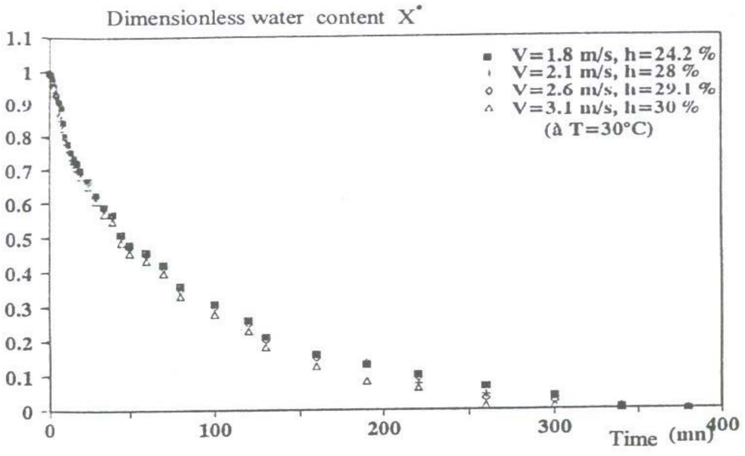

Fig. 9: Influence of the drying air velocity on the evolution of dimensionless water content as a function of time

3.3. Determination of the characteristic curve of drying

In order to determine the *characteristic curve of drying* (C.C.D), we apply the procedure developed by Voilley [9] by varying the experimental air conditions : drying air velocity, drying air temperature and air moisture content. Thus, we present, in figure 10, the dimensionless drying rate, given by the equation:

$$F = \frac{-\frac{dX}{dt}}{\left(-\frac{dX}{dt}\right)_i} \tag{1}$$

as a function of its dimensionless water content given by the equation:

$$X^* = \frac{\left(X - X_{eq}\right)}{\left(X_{in} - X_{eq}\right)} \tag{2}$$

for different air conditions.

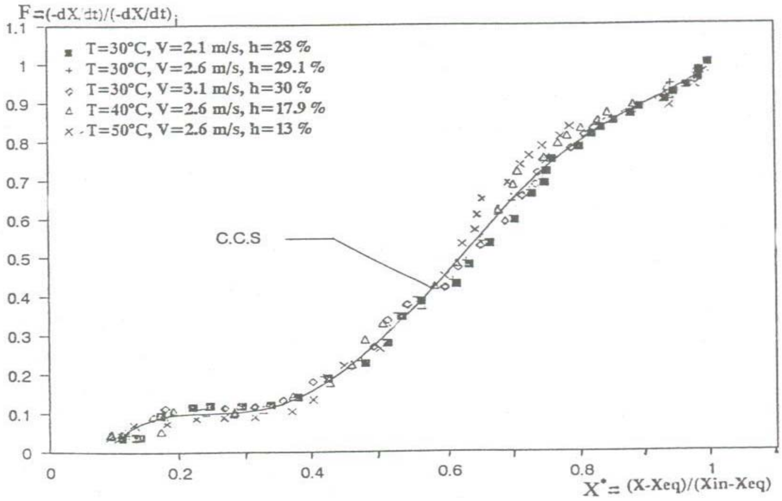

Fig 10: Characteristic curve of drying obtained for different air conditions

The equilibrium water content X_{eq} is determined from the isotherms of sorption [10]. The fitting of the curve representing equation (2) provides the *characteristic curve of drying*.. The C.C.D. takes into account the combined influences of air conditions. The equation expressing drying kinetics of a product is given by : F = F (X*). This equation takes into account the definition of initial drying rate $(-dX/dt)_i$ which must include the influence of external air conditions. This initial drying rate is defined by using the analogy between heat and mass transfer across the boundary layer of a completely wetted surface. To determine it, we suggest the relation established by Fornell [11] :

$$\left(-\frac{dX}{dt}\right)_i = \alpha V^{\beta}(T_a - T_h) \tag{3}$$

The smoothing of experimental data points gives the values of the constants α and β :

$$\beta = 0.43 \qquad \text{and} \qquad \alpha = 25.87\ 10^{-4}$$

Figure 10 represents the *characteristic curve of drying* obtained experimentally. It is a five degree polynomial equation that has the following form :

$$F = -0.35 + 6.21\,X^{*} - 31.824\,X^{*2} + 72.38\,X^{*3} - 68.71\,X^{*4} + 23.27\,X^{*5} \qquad (4)$$

4. DISCUSSION AND CONCLUSIONS

The study undertaken in this paper enables us to conclude that :

- There is absence of phase 0 (where the product temperature is increased without any substantial loss of water) and phase 1 (constant rate period) [12]. The drying temperature is the main factor controlling the rate of drying. It is an important parameter for internal water transfer in the product. This result is in perfect agreement with other published studies [5,6]. Bimbenet & al. [13] noted that the phase 0 disappears when the product is compact or in leaves and that the constant rate period (phase 1) is not observed in some biological products. This appears clearly in figure 3 which represent the variation of drying rate as a function of time. This curve follows a decreasing rate from the beginning of drying process.
- There is a perfect agreement between experimental results and theoretical predictions. The variation of air conditions seems to have no effect on drying kinetics at the end of drying process at which we note that the drying curves have tendency to coincide. At the falling rate period (phase 2 is the unique period observed in the drying of sage), the external air conditions have an influence which decreases until disappearing at the end of drying.

We have exploited our experimental results to determine the *characteristic curve of drying* (C.C.D) which is an important abacus giving precious information about the drying kinetics. The curve fit of C.C.D allows us to establish an empirical relation expressing the drying rate of sage for a large interval of drying temperature (between 30 °C and 50 °C). This equation is indispensable for the simulation and design of both solar and conventional dryers and also for the simulation of transfer phenomena taking place during the drying process [4, 14]. The objective is to control the factors affecting the total drying time of sage in a thin-layer solar drier operating by forced convection in realistic situations [15].

NOMENCLATURE

$(-dX/dt)_i$	: initial drying rate	Kg water / (kg *d.m* .s)
$-dX/dt$	: drying rate	Kg water / (kg *d.m.*s)
dm	: dry matter	
F	: dimensionless drying rate	
h	: air moisture content	%
M_d	: mass of dry matter	Kg
M_w	: mass of wet matter	Kg
T	: temperature of drying air	°C
Ta	: dry-bulb temperature	°C
T_h	: wet-bulb temperature	°C
V	: drying air velocity	$m.s^{-1}$
$X=(M_w - M_d)/M_d$	: water content (dry basis)	Kg water / (kg dm)
X_{in}	: initial water content (dry basis)	Kg water / (kg dm)

X_{eq}	: equilibrium water content	Kg water / (kg dm)
X^*	: dimensionless water content	

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