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KINETICS AND CHARACTERISTIC CURVE FOR CONVECTIVE AND INFRA-RED CONDITIONS DURING DRYING OF CLAY

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In this work, we present the experimental drying curves obtained by two heating modes, namely: convection and Infra Red. We examined the influence on the drying kinetics of the infrared flux density and of the aerothermic air condition: temperature, velocity and humidity. A comparison of the results obtained by the two heating modes are compared Finally, a polynomial equation was fitted to the experimental characteristic drying curve.
From the experimental drying kinetics the moisture diffusivity and the heat transfer coefficient values were identified.

Keywords: *internal diffusion, heat transfer*

Introduction

In many industrial processes, drying treatment generally, uses some conventional techniques of energy supply as convection and conduction. Nevertheless, these heat transfer modes have limit heat transfer capacities which can be inadequate for same separations.

Some "new" sources are found in radiative like Infra Red (IR), microwave, as the high frequencies technologies. The energy transfer to the product is direct and permits therefore to attain rapidly suitable levels temperature, which activates the fundamental drying mechanisms of the operation. Because of their performances, these techniques present currently a strong development.

The drying by Infra-Red radiation has been applied to several products like the agro-food products: [1-2], paint: [3] and pure and homogeneous materials: [4]. However, it is difficult to study the IR drying of foodstuff materials. They possess a complicated structure and, the knowledge of their optic properties is limited.

The effect of the emissivity of a deformable granulated bed during IR drying was investigated only in the constant rate period: [5-8]. Though for the drying of paper, the optic characteristics are better known, the problems bound to the effect of the geometry were not discussed in detail: [9]. However, it has been shown that geometric dimensions have a large influence on the functioning of the process: [10-11].

The IR drying rate depends essentially on the radiation absorption, on the density of IR flux and on some optic characteristics which vary with geometry, structure and water content. So, the main objective of our work was, to study the experimental IR drying curves and to compare these data the corresponding obtained with the convective drying.

Infra-Red Radiation

Before approaching the drying by IR, it is important to remind some useful essential properties as well as the principal advantages of IR radiation.

In fact, the IR radiation differs only from other electromagnetic vibrations: X rays, Ultra-Violet rays, visible light and hertzian waves, by its wave length which is included between 0.8μm and 15μm (*Table 1*). This physical characteristic distinguish IR from other radiations. However, the essential laws remain identical such as the phenomena of propagation, absorption and transmission.

In practice, one could not separate the IR and the visible radiation which are too near: one often detects some visible light in an IR drier.

The IR radiation in the range from 0.76μm to 15μm can be subdivided normally into three types:

- the short IR from 0.76μm to 2μm,
- the middle IR from 2μm to 4μm,
- the long IR from 4μm to 15μm.

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Table 1 Limits of wave of the Radiations

Type of radiation	γ Rays	X Rays	UV Rays	visible light	IR Rays	Hertzian Waves
Wave length limits	3.10^{-4}Å at 0.1Å	0.1Å at 200 Å	200Å at 0.4 µm	0.4µm at 0.8µm	0.8µm at 15µm	15µm at some km

If the processes of convective drying have already been the object of many studies, it is not the same for the mixed processes associating the convection and the IR heating, for which exists only very little literature in particular for the case of strong radiation densities, IR heating presents the following advantages:

- very high flux densities (up to 100kW/m²) and compact equipments,
- no direct contact with the product (dusts),
- possibility of focalising the energy,
- very response time which leads to easy control procedure.

Basis Concepts of Drying

Basic principles of convective drying are well known. Starting from a very wet capillary product, the moisture is moved to the surface under the form of a continuous liquid flux (capillary flow). The surface temperature of the product is constant (wet bulb temperature), so is the air temperature, hence the flux of evaporation remains constant. After a certain time, the capillary forces become inoperant to move liquid water from inside to the surface. New mechanisms of water displacement are found in surface diffusion, and evaporation-condensation cycles. The front between very wet material and almost dry material receeds towards the core of the product. IR radiation provokes an instantaneous drying of a thin superficial layer its temperature raising well above any wet bulb temperature. The results is then ambiguous: quick drying of a thin layer which in turn will slow down any water movement from inside. Thence the IR is reserved for thin materials or superficial drying.

Material and Method Infra-Red Drying

Experimental apparatus

Our drying experiences IR radiation is conducted by means of a device composed principally of:

- some emitters of IR energy,
- a sample placed at the bottom of the air tunnel,
- an electronic scale,
- excess air and steam exhaust.

Overall kinetics

The material was placed inside an aluminium cylindrical support. The mass and thermal exchanges were supposed unidirectional. The continuous weighting of the sample allowed to determine the drying kinetics. Several tests were achieved for different values of moisture and temperature (*Table 2*). Globally, experimental data presented on the following figures show distinctly:

Table 2 Some tests of drying by IR

Tests N	Air Temperature (°C)	Initial Moisture Content (kg/kg)
1	160	0.969
2	120	1.018
3	70	1.087
4	120	0.5843
5	160	0.72

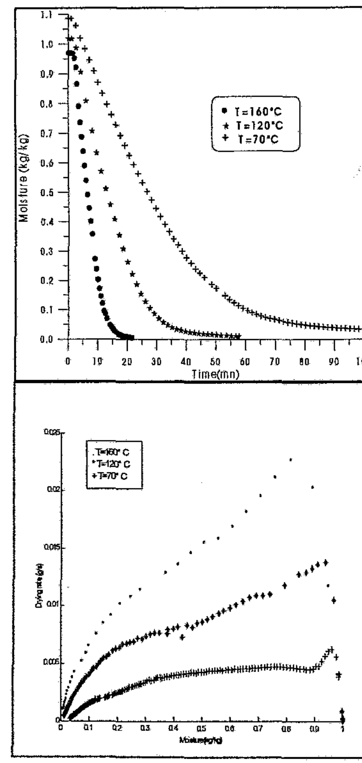

Fig.1 Influence of IR radiation on the kinetics of drying (Tests 1,2 and 3)

- at constant drying rate: period is sufficiently long and covers a large part of drying time. During this period, quite all the energy provided to the material was used for water evaporation,
- a decreasing rate period: it is very short and begins with the complete drying up of the surface of the material ; the temperature of the material increases noticeably. One supposes that the drying front receeds into the material.

Influence of Infra-Red Radiation

Under IR heating, the drying rate and therefore the water loss, depend directly on the incidental infrared flux.

In order to study the quantitative effect of the IR energy on the drying process, we applied different IR

Table 3 Some tests of drying by convection.

Tests N	Air Temperature (°C)	Air Humidity (%)	Air Velocity (m/s)	Initial Moisture Content (kg/kg)
1	37.5	22.1	2.3	0.49
2	50.8	50.8	1.5	0.538
3	55.7	16.9	2.3	0.69
4	48	20.8	2.2	0.433
5	54.9	13.9	1.6	0.76

flux densities to the clay and we recorded the sample mass versus time. As already noticed [10,13-16], we observed that the drying rate is proportional to the IR emitted flux (*Fig.1*) e.g.: the flux of matter is doubled when the power is doubled.

Convective Drying

Experimental apparatus

The experimental apparatus in which we conducted our tests of convective drying allowed to control the velocity, the temperature and the humidity of the drying air. It was made principally of:

- a simple aspiration ventilator with adjustable speed of rotation,
- some electric resistances for the heating of the air,
- of a humidifier/dehumidifier, allowing to maintain a constant humidity of air,
- of a sample holder into the vein of measurement on a balance, precision 0.1 mg. Data acquisition and treatment is insured.

Several tests were achieved for different values of moisture, temperature and air velocity (*Table 3*).

Influence of Air Temperature

The *Fig.2* shows that the drying kinetics increase with air temperature because of the increase of heat flux brought by the air to the product, and because the acceleration of the internal water migration bound to the coefficient of diffusion. One notes that the moisture content corresponding to the change of regime is so much more elevated when the temperature increases, whereas the equilibrium moisture content evolves in the opposite sense.

Influence of Air Moisture

An increase of the relative moisture entrains a reduction of the isenthalpic flux. The moisture content corresponding to the change of regime evolves in the same way as the isenthalpic flux. The equilibrium moisture content increases naturally with an increase of the relative moisture content (*Fig.3*).

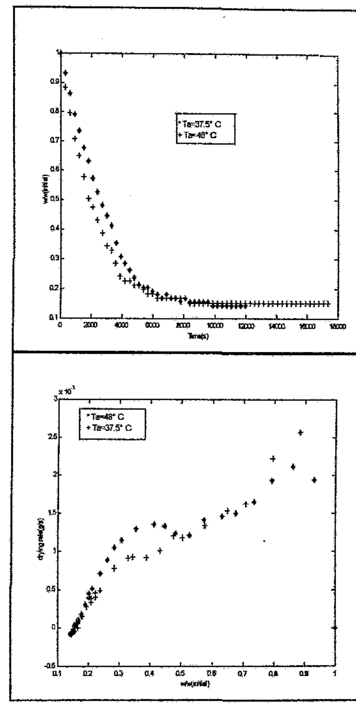

Fig.2 Effect of the temperature of the air on the drying kinetics (Tests 1 and 4)

Characteristic Curves of Drying

The method adopted for the determination of a master-curve, called characteristic curve of drying (CCD), is near in its principle to the one recommended by [11, 12-18], only used in the case of the products presenting a period of constant rate drying.

The purpose of CCD consists in establishing a law of drying based on some experimentation ; it derives from some basic knowledge acquired in the domain of drying but remains without complete theoretical justification. Consequently, only its aptitude to foresee some drying curves attests of its validity (heuristic approach).

A CCD results from the transform of the abscissa and of the ordinate in order to reassemble all the experimental curves (*Fig.4*) on a unique curve:

$$w \rightarrow \Phi = \frac{\bar{w} - w_{eq}}{w_{cr} - w_{eq}} \quad (1)$$

$$\left(-\frac{d\bar{w}}{dt}\right) \rightarrow f = \frac{-\left(\frac{d\bar{w}}{dt}\right)}{-\left(\frac{d\bar{w}}{dt}\right)_I} \quad (2)$$

The determination of a reduced variable curve after the transformation appears here very delicate because of the impossibility of reaching the values of $\bar{w}_{cr}$ and of $\left(-\frac{d\bar{w}}{dt}\right)_I$. We propose a new transformation, derived from the previous one:

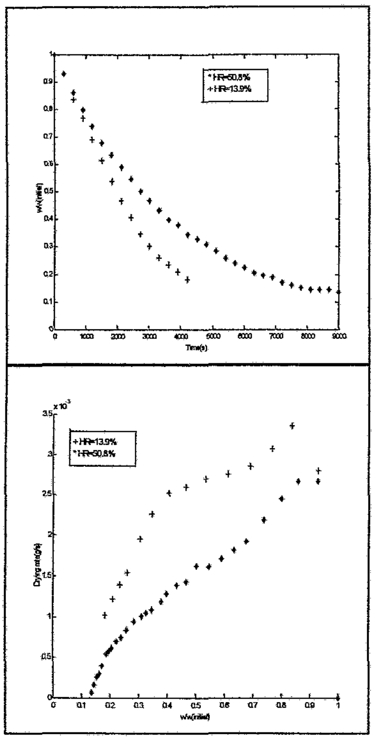

Fig.3 Effect of the moisture of the air on the kinetics of drying (Tests 2 and 5)

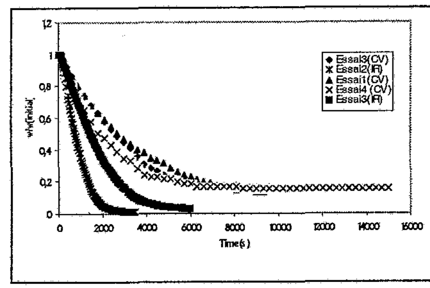

Fig.4 Comparison between convective and Infra-Red drying

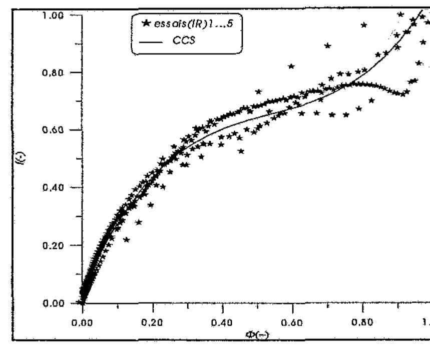

Fig.5 Characteristic Curve of drying of the clay

$$w \rightarrow \Phi = \frac{\overline{w} - w_{eq}}{w_0 - w_{eq}} \quad 0 \leq \Phi \leq 1 \tag{3}$$

$$\left(-\frac{d\overline{w}}{dt}\right) \rightarrow f = \frac{-\left(\frac{d\overline{w}}{dt}\right)}{-\left(\frac{d\overline{w}}{dt}\right)_0} \quad 0 \leq f \leq 1 \tag{4}$$

The application of this new transformation to the whole set of experimental curves of drying by IR radiation led the global *Fig.5*.

A polynomial interpolation of the experimental points led us to the following relation:

$$f = F(\Phi) = 2.7921\Phi^3 - 4.5175\Phi^2 + 2.7556\Phi + 4.0969 10^{-2} \tag{5}$$

Coefficient of Diffusion

The resolution of the model necessitates the knowledge of various physical properties of the clay among which the coefficient of diffusion is important.

In a general way, the coefficient of diffusion D intervenes in the expression of the temporal evolution of fields of the moisture (*Eq.(6)* and *(7)*):

If the product is not deformable, the equation reads:

$$\frac{\partial w}{\partial t} = \frac{\partial}{\partial x}\left(D \frac{\partial w}{\partial x}\right) \tag{6}$$

If the product is submitted to a unidirectional shrinkage it becomes:

$$\frac{\partial \mathrm{w}}{\partial t} = \frac{\partial}{\partial \xi}\left(\frac{\mathrm{D}}{(1+\varepsilon \mathrm{w})^2} \frac{\partial \mathrm{w}}{\partial \xi}\right) \tag{7}$$

Extracting diffusion coefficients as a function of moisture content from drying curves is very difficultand does not produce satisfactory results. KETELAARS attributes this difficulty to the fact that drying curves are sensitive to the moisture concentration dependency of the diffusion coefficient in a limited range.

Outside this region, the diffusion coefficient has little to no value. Only diffusion coefficient derived from internal moisture profiles are valuable.

Our clay sample G is very similar to clay A used by [24], as their shrinkage curves are similar. With both w_r shrinkage limits are in the vicinity of 0.25.

Nevertheless, we have tried to identify a coefficient of diffusion from drying curves for values of $w<0.1$. Our two results fit in rather well with KETELAARS, values near $10^{-9}\ m^2s^{-1}$ *(Fig.6)*. A possible expression for the coefficient of diffusion is:

$$D(w,T) = D_o\left(\exp\left(\frac{aw}{b+w}\right)\right)\exp\left(-\frac{c}{T}\right) \tag{8}$$

with D_o, a, b and c parameters for adjustment (*Table 4*).

Heat and Mass Transfer Coefficients

The CHILTON-COLBURN analogy is largely used in drying studies. Indeed, if one admits that the temperature and vapour concentration boundary layer are very similar, the convective coefficients heat h_c and mass k_m are related by the LEWIS relation of:

Table 4 Values of parameters of diffusion

D_o (10^{-10} m²s⁻¹)	a	b	c
4.61	1.8019	0.031	16

$$\frac{h_c}{k_m \rho C_p} = f(Le) = \left(\frac{Sc}{\Pr}\right)^{2/3} \qquad (9)$$

So, the mass transfer coefficient value k_m can by derived from h_c, values which are generally calculated from some classical empirical heat transfer correlation.

The validity of this pure convection analogy in presence of IR radiation and an important flux of matter was discussed and checked by [17].

Transfer of Heat by Convection

The film theory allows to express the flux of heat through a boundary layer of steam by the relation:

$$Q_{conv} = \frac{L_v}{Cp_v} h_c Ln\left(1 + \frac{Cp_v(Ta - Tsurf)}{L_v}\right) \qquad (10)$$

In the case of a drying with a weak rate of evaporation, the flux of sensible heat is very much lower compared to the fluxes of latent heat in such a way that one gets:

$$Ln\left(1 + \frac{Cp_v(Ta - Tsurf)}{L_v}\right) = Cp_v \frac{Ta - Tsurf}{Lv} \qquad (11)$$

This equation is then equivalent to *Eq.(12)* of common use:

$$Q_{conv} = h_c(Ta - Tsurf) \qquad (12)$$

Convective Heat Transfer Coefficient

If the hydrodynamic and aero thermic regime is well established, the heat transfer coefficient can be estimated from well known relationships:

a. *Forced convection*

DITTUS BOELTLER proposed the following relation taking into account some secondary side effects:

$$Nu = 0.023 \mathrm{Re}^{0.8} \Pr^{1/3}\left(1 + 6\frac{D_h}{L}\right) \qquad (14)$$

where D_h and L are respectively the diameter and the length of the duct.

b. *Natural Convection*

From the GRASHOF's work, one may use:

$$* \; 3.10^3 < \mathrm{Gr} < 10^8 \longrightarrow Nu = 0.27(Gr\Pr)^{1/5} \qquad (15)$$

$$** \; 10^8 < \mathrm{Gr} < 10^{10} \longrightarrow Nu = 0.27(Gr\Pr)^{1/4} \qquad (16)$$

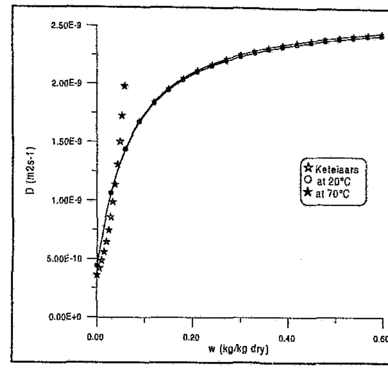

Fig.6 Evolution of diffusion coefficient with the moisture content

with: $Nu = \frac{h_c D_h}{\lambda}$; $\mathrm{Re} = \frac{VaD_h}{\nu}$; $Gr = \frac{\beta g(Tp - T\infty)D_h^3}{\nu^2}$,

ν: kinematic viscosity (m²s⁻¹),

β: air compressibility.

c. *Equivalent Radiative Heat transfer Coefficient*

$$\begin{aligned} Qr &= \sigma(T_{surf}^4 - T_a^4) = \\ &= \sigma(T_{surf}^2 + T_a^2)(T_{surf} + T_a)(T_{surf} - T_a) = \\ &= h_r(T_{surf} - T_a) \end{aligned} \qquad (17)$$

Mass Transfer Coefficient

According to NAVARRI, the coefficient of transfer is independent of the presence variation of the IR flux. In the case of the humid air, $\left(\frac{\Pr}{Sc}\right)^{2/3} \cong 1$, so it is possible to estimate the mass transfer coefficient:

$$k_m = \frac{h_c}{\rho Cp} \qquad (18)$$

As checked by [17], this analogy also could be applied in the case of IR drying.

However, the previous analogy applies only in the case of pure convective heat transfer. In this study and as a measure of simplification, we supposed that the analogy applies to the global coefficient of transfer ($h=h_c+h_r$) which is a convenient coefficient for the experimental reality.

Conclusion

In this work, we studied the clay drying kinetics by two different heating modes: convection and IR radiation.

In the case of convective or IR heating, the drying kinetics show two drying periods departed by the critical moisture content.

The increase of the drying air relative humidity decreases the drying rate in the case of convection, contrary to the case of IR heating for which this humidity does not have a significant influence.

The increase of the air temperature enhances appreciably, in as much as it is tolerated by the product, the drying rate during the constant rate period.

The increase of the IR generally flux density implies a very height increase of the drying rate, which reduce the drying time and preserving the quality of the product (*Fig.4*).

The concept of characteristic drying curve was checked in order to an overall expression of the drying kinetics. By using an appropriate change of variable, one could determine an empiric expression of the drying kinetics suitable to control and predict the drying process independently of the chosen parameters.

In spite of a satisfactory, essentially for small moisture content, identification of the material diffusion coefficient from the kinetics, we will adopt the KETELAARS results in the numeric part. As for the coefficients of thermal transfer, we will apply the analogies generally admitted.

SYMBOLS

C	specific heat, $Jkg^{-1} K^{-1}$
D	diffusion coefficient, m^2s^{-1}
h	heat transfer coefficient, $Wm^{-2}K^{-1}$
k	mass transfer coefficient, ms^{-1}
Le	Lewis number, -
Nu	Nusselt number, -
Pr	Prandtl number, -
Q	heat flux, Wm^{-2}
T	temperature, K
t	time, s
w	moisture content, $kgkg^{-1}$

Indexes

c	convective
cr	critical
eq	equivalent
o	initial

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