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AMELIORATION DE LA QUALITE AGRO-INDUSTRIELLE DU MAIS PAR LA MODELISATION DYNAMIQUE DU SECHAGE

Francis Courtois

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Dynamic Modelling of Drying to Improve Processing Quality of Corn

Dr Francis Courtois

April 1997

Preface

To refer to this work use one of these :

- **COURTOIS F., 1991. Amélioration de la qualité agro-industrielle du maïs par la modélisation dynamique du séchage, mémoire de doctorat, ENSIA, Massy, France.**
- **COURTOIS F., 1991. Dynamic Modelling of Drying to Improve Processing Quality of Corn, PhD thesis report, ENSIA, Massy, France.**

This report is a translation of the french PhD thesis in Food Engineering dated september 1991 (see figure 1). The previous version was written on *Word 5.1 for Macintosh*. It has been translated from French to English using *PowerTranslator for Macintosh* then hand-corrected. This report is now reformatted as a Latex document available freely through the Internet at

<<http://ensia.inra.fr/~courtois/welcome.html>>

or by email to

courtois@ensia.inra.fr.

A few minor corrections have been done so that it cannot be considered as an updated version of the original report.

This work is copyright of Francis Courtois and ENSIA. Financial support from ITCF, CIFRE and ADEME should be acknowledged.

The author wish to thank J.C. Lasseran and A. Lebert for their unmeasurable help. This work couldn't have been done without them.

Special thanks also for ITCF and ENSIA's Food Eng. Dept. teams.

To Anne, my wife, with love... Could someone be as patient as you were ?

THESE

Présentée

**l'Ecole Nationale Supérieure des
Industries Agricoles et Alimentaires**

pour l'obtention du grade de

DOCTEUR

de l'ENSA - Spécialité Génie des Procédés

par

Francis COURTOIS
Ingénieur ENSIA

sur

**AMELIORATION DE LA QUALITE AGRO-INDUSTRIELLE
DU MAIS PAR LA MODELISATION DYNAMIQUE DU SECHAGE**

Thèse soutenue le 27 septembre 1991 devant le jury composé de :

Professeur	RIBA J.P.	Président
Professeur	ARVALIN G.	Rapporteur
Professeur	BIMBENE T.J.J.	Rapporteur
Monsieur	LEBER A.	Examineur
Monsieur	LAFFRAN J.C.	Examineur
Monsieur	BLANDIN C.	Examineur

Travail réalisé au Service "Qualité et Débouchés Agro-Alimentaires" de
l'Institut Technique des Céréales et des Fourrages

Figure 1: Official french title page

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Summary

Maize is, in France, the second agricultural produce after wheat. To be acceptable for the industry, it has to preserve all its qualities during the drying period following harvesting. Required to reach the biochemical and biological stability of the product, the drying operation can involve a loss in wet-milling quality which is a criterion largely considered in the maize industry nowadays.

Thus it became important to consider, in addition to energetic yield and evaporation rate criteria, the wet-milling quality of the maize in order to optimize dryers design.

Automatic control is a modern way to optimize the dryer "real-time" management.

The objective of this work is to build up a simulation tool helpful for the design of dryers and control algorithms optimized with regards to energy, grain flow and quality.

The influence of a thermal stress on wet-milling quality is modelled. The quality equation thus defined is used in a drying dynamic model based on a compartmental method and developed from the thin layer to the industrial dryer scale.

The model, adjusted on drying kinetics under constant conditions, is used to predict the steady state of any dryer. It allows the modelling of any transient phenomena happening in industrial dryers : sudden changes in air temperature, drying breakdowns, cooling, condensation, air recycling...

This model is also used to predict the dynamic behaviour of dryers when a disturbance is applied and thus to test the applicability of control algorithms.

From the thin layer to the industrial dryer, simulations are compared to experimental results. A 5% mean error on the predicted moisture content of dried corn is obtained. The error on the wet-milling quality prediction is of the same order than the error due to the followed experimental procedure.

Key words

corn, drying, grain, maize, compartmental model, dynamic, wet-milling quality, simulation, automatic control.

Symbols

Acronyms

AGPM	Corn Productor Association
AFRC	Agricultural and Food Research Council
CEMAGREF	Technical Institute for Agricultural Engineering
ENSIA	High School for Food Engineering
ITCF	Technical Institute for Cereals and Fourrages
TPI	Irreversible Thermodynamics

latin letters

a	grain surface area / volume ratio (m^{-1})
a_R	parameter of AFRC's controller
A_g	single grain surface area (m^2)
A_w	water activity in compartment 3 †
B_i	water exchange coefficient between compartments i and $i + 1$ ($kg.s^{-1}.m^3$)
c_p	specific heat at constant pressure ($J.kg^{-1}.K^{-1}$)
D_{ij}	water flow rate between compartments i and j ($kg.s^{-1}$)
E_a	activation energy in Arrhenius law ($J.mol^{-1}$)
H	enthalpy (J)
K_{ij}	water exchange coefficient between compartments i and j ($kg.s^{-1}$)
K_Q	quality coefficient (s^{-1})
K_R	parameter of AFRC's controller ($kg^{-1}.m^2.s$)
L_v	latent heat of vaporisation ($J.kg^{-1}$)
n	order of the reaction kinetic †
P	pressure (Pa)
Q	wet-milling quality as a result of the turbidity test (absorbance)
R	perfect gas constant ($8.3143J.mol^{-1}.K^{-1}$)
S	dryer section (m^2)
t	time (s)
T	temperature ($^{\circ}C$)
V_a	air velocity ($m.s^{-1}$)
V_g	volume of one grain (m^3)
X	grain moisture content (dry basis) †
Y	air moisture content (dry basis) †
z	abscissa along air flow axis (m)

grec letters

α	convection heat transfer coefficient ($W.m^{-2}.K^{-1}$)
β_p	mass transfer coefficient related to pressure ($kg.m^{-2}.Pa^{-1}.s^{-1}$)
ϵ	bed porosity †
Φ_m	mass flux density between air and grain ($water\ kg.m^{-2}.s^{-1}$)
Φ_c	heat flux density between air and grain ($W.m^{-2}$)
ρ	density of dry product ($kg.m^{-3}$)
τ_i	volume ratio of compartment i †

subscripts

0	initial
1	central compartment
2	medium compartment
3	peripheral compartment
<i>a</i>	air
<i>ahc</i>	air outside the layer
<i>f</i>	final
<i>g</i>	grain
<i>t</i>	at time t
<i>v</i>	vapor
<i>vsat</i>	vapor at saturation
<i>w</i>	water

†No dimension

Introduction

Second French vegetable production, the corn represented in 88/ 89 (figure 2) a production of $14.4 \cdot 10^9$ kg including the export of $7.8 \cdot 10^9$ kg (AGPM, 1989).

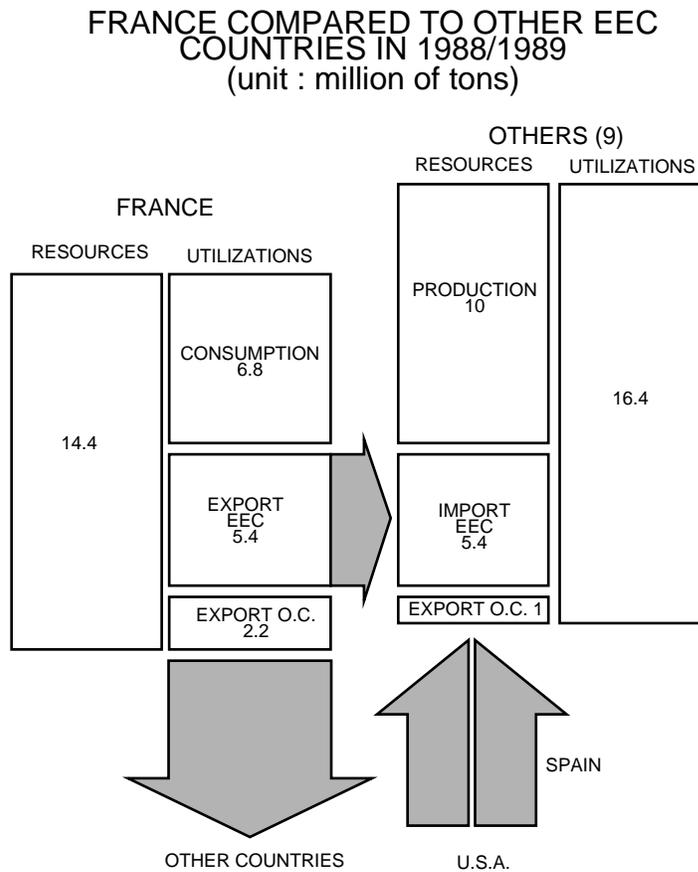


Figure 2: The corn in the EEC (AGPM, 1989).

The grain, to be stored, should first be dried down to a humidity between 14 and 15% (wet basis): it is the role of the drying. Indeed, the stocking of the humid grain provokes alterations:

- loss in germination viability,
- growing of mildews which may generate toxic substances,
- loss of dry matter due to biological activity.

This last point is very important when one knows that the corn is paid, indirectly, to the dry matter weight.

As an example, a grain at 30% of humidity has a biological activity 400 times more important than those at 15%.

Corn is dried, in collector organisms, on large industrial dryers. The high debits of these dryers oppose well often to the production of a grain of high quality, usable by processing industries : starch and semolina industries mainly (figure 3), whose demand is in constant growth (25 to 50% depending on the geographical zone). It results in a potential competition with American corn (imported directly or through the Spanish market) and south-European corn (Italy, Greece), less dried because being harvested at a weaker humidity, therefore of a priori better quality.

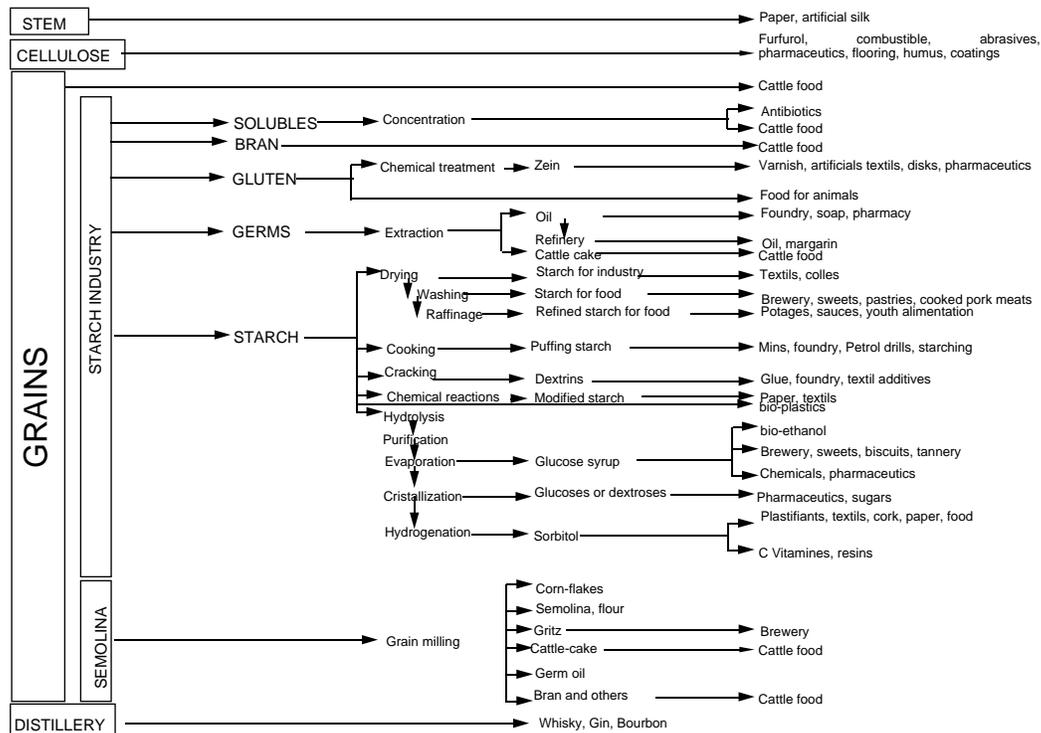


Figure 3: Corn outlets (AGPM, 1989).

The "wet-milling quality" of the dried corn has become both an objective and a constraint for these industries. And it is well established that the first factor of degradation of the corn wet-milling quality is drying. This explains the need for corn dryers thrifty in energy, to have a large evaporation capacity and to preserve the dried grain quality.

Causes of the degradation of the wet-milling quality are examined later (chapter 1). But the main actor of the degradation is well known: it is the "drying time - grain temperature" couple ; one notes also a strong influence of the grain moisture content on the effects of the time-temperature couple. Due to the lack of a quantitative simulation tool, one considers generally that it is necessary to decrease the drying (air) temperature to obtain an acceptable wet-milling quality, but it is to the detriment of the production capacity.

One of the problems comes from the fact that farmers harvest all at the same time: the cooperative is then submitted to a massive grain rush that it can not always dry immediately. This is why one observes often a temporary humid storage, in conditions going from the simple heap in the yard to the inerting in hermetic cells. That always provokes a degradation (decline of the wet-milling quality, dry matter loss, mildews...).

The quality of the grain is therefore depending, in a lesser measure, on the rapidity of the passage of the crop in the dryer.

To face the massive grain rush, several practical solutions are used:

- to increase the capacity of drying by adding supplementary dryer(s) or replacement by a largest one, but the overcost is not always amortized,
- to change the configuration of dryers (functioning in series instead of in parallel...), to make the tempering (rest of the grain in cell without ventilation)...
- pre stocking in cell with continuous ventilation but the grain quality declines,
- to increase the temperature of drying to increase the dried grain flow, unfortunately the wet-milling quality decreases very rapidly while risks of fire grow,
- to obtain a dried grain 18 and 19% of humidity ending its drying with a "dryeration" (ventilation of the grain in cell after a relaxation), it is very advantageous but not always possible.

Indeed, ITCF studies (LASSERAN, 1977) have shown that the utilization of the dryeration or the tempering decreased the degradation of the grain while increasing the output. Because the grain resting is accompanied by a re equilibration of its humidity accelerating the next drying ; it is necessary therefore to take into account the grain internal gradients.

The challenge for France is therefore triple. It is necessary to conceive dryers whose:

- costs of functioning remain the weakest,
- drying capacity is maintained,
- quality of the dried grain is improved.

In fact the dryer improvement or the experimentation of new designs are expensive. In besides, the recent shortened campaigns of harvests (and therefore drying), 4 to 6 weeks depending on the regions, limited test possibilities.

One better understands the interest to have a dryer simulation model responding to problems of:

- design and arrangement of elements of a dryer,
- optimization of the functioning of the drying in a broad sense (tempering...);

and that with two points of view : productivity and quality.

Considering the specificities of French dryers (detailed in chapter 4), the following aspects should, in addition to the quality degradation, be taken in account:

- transitory aspects (changes of air temperature),
- relaxation aspects,
- cooling aspects,
- air recirculation,
- rewettings.

Our study comes later than that of DAUDIN (1982). On all points previously listed, only the air recirculation is taken in account by its model.

Very few drying models integrate the quality, whatever it is, and in fact, none concerns corn. The closest study concerns the germination viability of the wheat (NELLIST, 1981) on English dryers producing seeds. Furthermore, there exists no relative thorough experimental study about the influence of the drying on the corn wet-milling quality. The essential of the knowledge on this subject is concentrated at the ITCF. In fact, in the course of this study, STEINMETZ, at the ENSIGC of Toulouse, has started a research concerning the impact of the drying on the corn wet-milling quality with a different quality criterion and a different methodology.

Furthermore, there is no true dynamic model (valid in transitory regime). Generally, models are based on an empirical equation adjusted on the kinetics in constant conditions (BAKKER ARKEMA and al., 1974). They are therefore unadapted to simulate a French industrial corn mixed-flow dryer.

This explains that there is no drying model practically capable to simulate stops and jumps of drying.

Moreover, models integrating the moisture content gradient within the grain are generally long to calculate and complex to identify (ABID and al., 1988). Their utilization for the simulation of dryers requires a powerful computer.

In the beginning of this study, it existed very few theoretical researches concerning problems of grain or air flows (TOFTDAHL OLESEN, 1987). Later, work of ARNAUD and FOHR at Poitiers and those of FLICK and CHAABOUNI at Antony have allowed to increase our knowledge about these problems. However, their approach does not aim, for the moment, to simulate completely the dryer functioning.

Finally, there exists very few works aiming to use a drying model for the dryer control (WHITFIELD, 1987a). This comes from the fact that a dynamic model is practically required.

Our study had for objective the development of a tool for static or dynamic optimization, design, adjustment and control of dryers. The model had to allow, in addition to the classic production, energy consumption and product humidity criterion, to take into account the quality factor.

Our work has begun with the development of a quality equation. This equation is then combined with a dynamic model of the drying of corn thin layers. It is based on a compartmental approach. Transfer coefficients are identified with the help of kinetics under constant conditions.

The numerical resolution of the drying in deep beds has necessitated the use of complex methods. Nevertheless, several simplifying hypotheses have allowed to obtain a rapid method whose results are identical.

The method of decomposition of the dryer in deep beds is then described. The application is realized on the ITCF experimental dryer which can be considered as an industrial dryer at a 1 / 4th scale. Simulated data are analyzed through the use of curves.

Finally, the dynamic model is used to study the dynamic behavior of a dryer and to adjust and test an automatic control algorithm. This algorithm is adapted from that developed by AFRC for the control of wheat dryers.

For each chapter, results obtained with the help of successive models are compared, as much as possible, with experimental results.

This work led to the following publications and communications:

- COURTOIS F., LEBERT A., DUQUENOY A., LASSERAN J.C., BIMBENET J.J., 1991, modelling of Drying to Improve Processing Quality of Maize, *Drying Technology*, 9(4), pp 927-945.
- COURTOIS F., LEBERT A., DUQUENOY A., LASSERAN J.C., BIMBENET J.J., juin 1989. Modélisation du séchage du maïs, 4ème Colloque Université-Industrie, Marseille, pp. 121-132.

- COURTOIS F., LEBERT A., DUQUENOY A., LASSERAN J.C., BIMBENET J.J., 1990, modelling of drying in order to improve processing qualities of maize, 7th International Drying Symposium IDS'90, Prague.

Important Note:

This memory comprises 4 chapters chaining logically. Each of them has a typical article structure and is, to a certain extent, autonomous.

Chapter 1

Modelling of the quality degradation

1.1 Bibliography

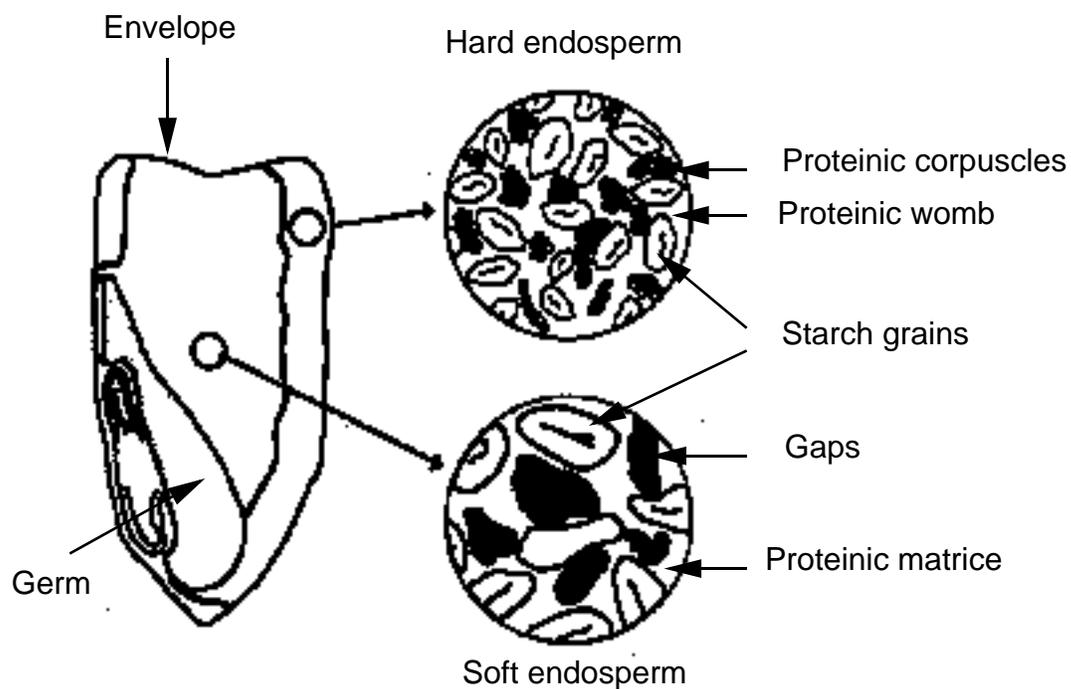


Figure 1.1: Constitution of a corn grain according to LE BRAS (1989).

The corn grain is composed of 3 elements (figure 1.1):

- the envelope (approximately 5% of the dry matter),
- the endosperm or albumen (approximately 85% of the dry matter) that contains most of the grain starch and proteins,
- the germ (approximately 10% of the dry matter) containing most of the grain lipids and functional proteins.

The endosperm, or albumen, can be divided into 2 distinct parts (LE BRAS, 1989):

- the hard or vitreous endosperm constituted of a dense system of starch and proteinic grain corpuscles; situated in periphery, it is the most exposed part to the drying,

- the soft or floury endosperm constituted of a loose system of large starch grains embedded in a proteinic womb comprising gaps or vacuoles filled with water when wet.

Proportions of these 2 parts vary from a variety to another.

LE BRAS (1989) considers on the one hand that the heat + dehydration combination within the vitreous endosperm is propitious to the contraction of the protein womb (imprisonment of starch grains) and to the proteins coagulation seeing their density increasing from 1.3 to 1.4. And, on the other hand, that the combination of heat + humidity within the floury endosperm is propitious to the starch gelatinization (from 60°C) seeing its density decreasing from 1.5 to 1.4.

In fact many other phenomena happen during drying:

- degradation of the lysin and some other amino-acids, forming of di-sulphid bridges... (WALL *et al.*, 1975; LUPANO and DONKEY, 1987)
- migration of the germ oil to the endosperm periphery, browning of the grain (LENOIR and ALAIN, 1988)...
- detachment of membranes and forming of fissures linked to the mechanical stress undergone by the grain (FARBER, 1976; GUNASEKARAN and PAULSEN, 1985)

It is necessary to note that these fissures accelerate the heat flow penetration within the grain kernel and therefore its degradation.

To the extent of the market value of the corn quality being influenced by the presences of cracks or broken grains, some authors have tried to study the evolution of the mechanical tension within a corn grain submitted to high temperature drying. Studies are experimental (GUSTAFSON and MOREY, 1979; GUNASEKARAN and PAULSEN, 1985; ITUEN *et al.*, 1986) or quite theoretical (GUSTAFSON *et al.*, 1979; HAGHIGHI and SEGERLIND, 1988a; LITCHFIELD and OKOS, 1988) using a model often very complex. And unfortunately, there are few comparisons between simulations and experiments. The air temperature seems to be however the preponderant factor of this mechanical degradation.

The wet-milling quality of the corn is simply defined by the output of the endosperm starch / proteins separation. The figure 1.2 represents the functional diagram of a wet milling plant : the process operates with liquids, mainly suspensions. Separations are based on the differences of density between constituents, particularly in the case of the centrifugation of the starch + proteins suspension in a series of hydrocyclons (LE BRAS, 1989).

A first test of wet-milling quality of a dried corn sample would consist therefore in a measure of the output of the starch/proteins separation or the purity of the starch fraction, with the help of a wet-milling pilot-plant allowing to process small quantities. This test is currently developed at the ITCF (laboratory of A. LE BRAS). One can consider that it is the reference method to measure the wet-milling quality of the corn.

More simply, there exists a test called "sedimentation test" that presents the advantage to enable the process of smaller quantities (200 g) but necessitates at least 4 hours to obtain the result and has a poor precision (visual evaluation). The principle, simple, consists in a decanting in a graduated cylinder of a starch and protein suspension extracted from grinded corn. STEINMETZ (1990) and its team have retained this test as a wet-milling quality criterion for their study on the corn but seem confronted with practical problems in its application.

An indirect test, but of more well-off application: the "turbidity test", represents the thermal past of the grain. It is based on the measure of the saline water soluble (heat-sensitive) proteins by spectrophotometry. The principle, simple, consists in extracting these proteins from grinded corn in a saline water solution then to coagulate them at 100°C and to measure the opacity of the solution. It is necessary

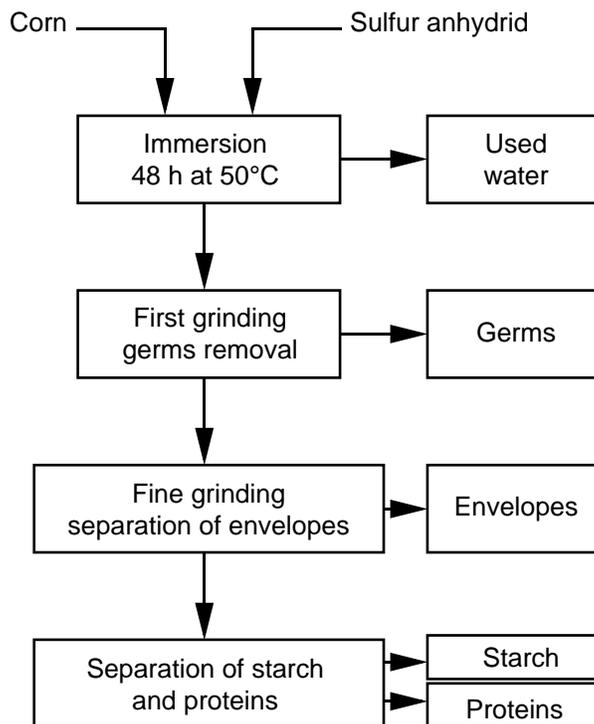


Figure 1.2: Functional diagram of the wet-milling process from LE BRAS (1989).

to note that the word "turbidity" is inappropriate since we consider the percentage of light transmitted through the solution. This test is very popular because it necessitates no more than 25 g and gives a result within 15 minutes approximately.

Although saline water soluble proteins, albumin and globulins mainly, represent only 15% of total proteins of the grain and are situated for 70% in the germ (LANDRY, 1979), they allow well enough to discriminate corn samples and to classify them in term of output, or better, rate of starch recovery and therefore of "wet-milling quality".

Since our work is centered on the modelling and not on the selection or the development of a quality test, it is this test that we have retained and, thus, "quality" will be assimilated as the "result of the turbidity test".

It is necessary to notice that there exists several other tests more or less rapid and reliable (LASSERAN, 1991) but the former is obviously the most used.

Most of authors agree to recognize that the first factor of degradation of the corn is the air drying temperature, they even recommend maximal temperatures according to the desired quality: LE BRAS (1989), NELLIST (1981) considering germination viability of wheat seeds. FREEMAN (1973) asserts, as for he, to have observed that a corn was all the more damaged that it is more humid but it is necessary to remind that the drying duration, and therefore the heat exposure, increases, for a same objective, with the initial product humidity.

Finally, it appeared interesting to be able to study separately the influence of each important variables: quality Q , time t , temperature of the grain T_g , moisture content of the grain X , on the degradation of the quality. It is the interest of the methodology of NELLIST and BRUCE (1987) used for the modelling of the germination viability degradation and the baking-ability of the wheat during its drying. The principle and the application are very simple: a thin layer (mono-granular) of product is enclosed in an vacuum-sealed hermetic sachet, this sachet is submitted to a thermal stress at constant moisture content by immersion in a water-bath. This method allows to vary only one parameter at a time since the product

does not dry, and facilitates therefore the analysis of the results. One will retain that its main defect is to make the hypothesis that phenomena are identical -at least from a qualitative point of view- during a thermal stress with or without drying. Anyway, it is the simplest way to obtain the necessary knowledge basis for the establishment of the model.

The result of the test, noted Q , if expressed in absorbance units, is therefore correlated with the protein concentration in the saline solution extract. One can therefore write a priori:

$$\frac{\delta Q}{\delta t} = -K_Q \cdot Q^n \quad (1.1)$$

where

- K_Q is the coefficient of the kinetic of degradation assimilated to a unique chemical reaction. Generally, this coefficient is connected to the temperature T_g by an Arrhenius law depending on the moisture content X . And
- n is the order of the kinetic: generally 0, 1 or 2.

It is the most used manner to model experimental degradation curves of the quality during the drying: KAREL *et al.* (1987) for the C vitamin in potatoes, NELLIST and BRUCE (1987) for the baking quality of the wheat, SOKHANSANJ *et al.* (1985) for the germination viability of the wheat...

Note that the approach of SOKHANSANJ *et al.* (1985) is interesting in the sense that it aims, by a stochastic approach, to express the dispersion of simulated results around the average by taking into account the natural variability of grains (moisture content, germination viability...).

NELLIST (1981), LESCANO and TYRRELL (1987), as well as many other authors, have used a probabilistic method to account for the germination viability degradation of grains during drying. The percentage of germination of a dried grain sample is represented by a normal law depending on the time of drying and a standard deviation of degradation that is related to drying conditions (numerical adjustment).

One will retain that stochastic methods have the advantage to bring the notion of result dispersion around their average what is perfectly adapted to biological products, but that they necessitate generally more experiments and time of calculation than deterministic models. This is why we have preferred to develop a deterministic model.

1.2 Material and methods

1.2.1 Origin of the corn

It is essentially the corn from the ITCF-BOIGNEVILLE whose variety is DEA (flint-dent type) hand-harvested and hand-shelled, that has been used, but also:

- the corn from the Cooperative of Dormans (51), DEA variety (flint-dent type),
- the corn from the Cooperative of high Normandy (27), DEA variety,
- the corn from the southwest of France, VOLGA variety (dent type).

The conservation has been made in a cold chamber (in cob or in grain) and the obtaining of a given humidity, or conditioning, by a slow drying in a conditioner : dryer at low temperature (less than 30°C).

Prior ITCF studies had, indeed, shown that the storage in cold chamber on short periods and the conditioning had no influence on the quality of grains.

1.2.2 Rewetting of the corn

For some experiments, especially to obtain grain moisture content higher than 0.430 (30%, wet basis), it has been necessary to rewet two corn types:

- corn harvested at low humidity during the campaign,
- corn stored and dried naturally in cob (in cribs) for delayed experiments.

Grains are left soaking in the distilled water during approximately 24 h, at ambient temperature (0 to 20°C), stirring from time to time. The corn is then driped and left to rest during at least 24 hours to allow a re-homogenization of its moisture content and a light superficial drying: this corn should have the appearance and the consistency of a naturally humid corn. One can approach a particular moisture content by a conditioning and a regular control of the evolution of this parameter.

In fact the method of rewetting, that few authors specify, varies appreciably with practical constraints met.

1.2.3 Methods of moisture content determination

The precise method (called "practical method on whole grains", AFNOR norm V03-708), used at the ITCF, is based on the measure of the consecutive weight loss to a 38 hours stay at 130°C (CHOPIN cellular oven) of approximately 15 g of whole grains in an open cupel.

One obtains then the corn moisture content in kg of water by kg of dry matter (i.e. dry basis):

$$X = \frac{\textit{Weighing before oven} - \textit{Weighing after oven}}{\textit{Weighing after oven} - \textit{Tare}}$$

The machine "CHOPIN rapide" summarizes the same principle but with approximately 5 g of pounded corn grains, at 210°C during 5 to 10 minutes. The vaporized water passes through a cylinder containing the carbide of calcium and reacts with it to give a flammable gas. The disappearance of the flame corresponds therefore with the end of the vaporisation. This method is almost as reliable as the precedent for a complete execution time of less of 15 minutes.

To obtain a precise humidity, one uses also electronic machines, less precise but very rapid, based on the principle of a dielectric measurement (SUPERMATIC by FOSS-ELECTRIC, MULTIGRAIN by DICKEY-JOHN...).

1.2.4 The "turbidity test"

The figure 1.3 reminds the general principle of the operative mode described in LE BRAS and BEAUX (1984) with its 2 scales of notation. One will retain that (LE BRAS and CHARENTON, 1989):

- The result is expressed in percentage of light transmitted through the solution (%T).
- The moisture content of the corn has to be between 0.150 and 0.205 without what the fine grinding can not work correctly (high deposit on the sieve).
- The extraction doesn't operates in a buffer (controlled pH) solution what seems very constricting for proteins; moreover the quality of the arabic gum is not stable.
- The result of the test is very sensitive to the respect of duration of the grinding, the extraction and the immersion at 100°C.

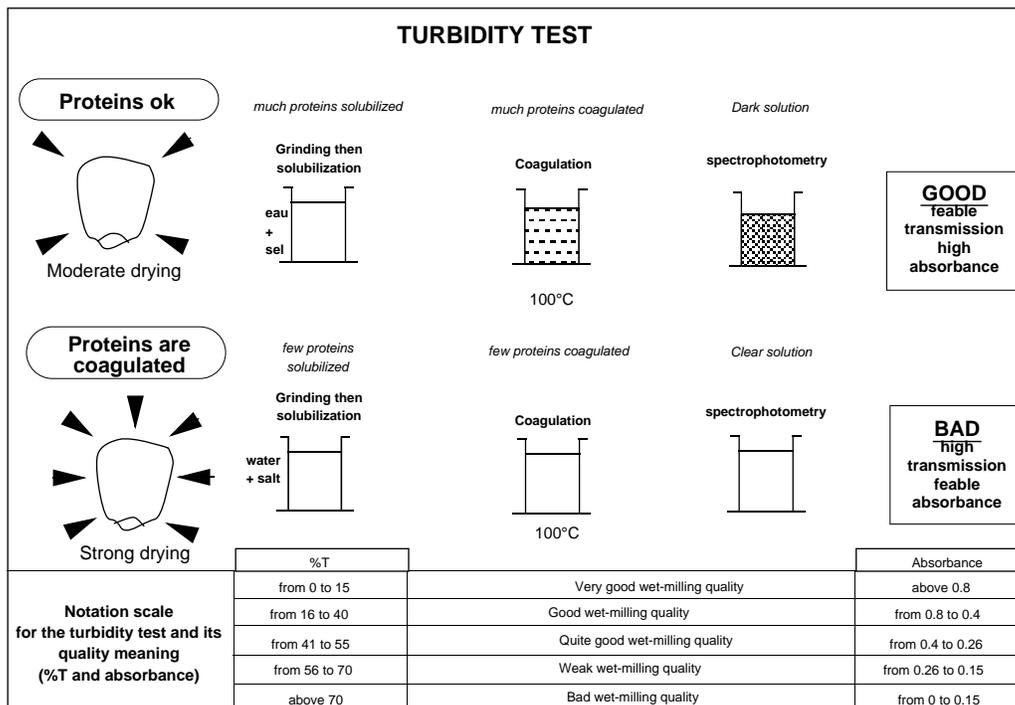


Figure 1.3: General principle of the turbidity test and scales of notation according to LE BRAS (1989).

- The result of the test is very sensitive to the efficiency of the cooling after immersion to 100°C.

A study (LE BRAS, 1982) has shown that if the standard deviation of the repeatability (on the result expressed in transmitted light percentage) is not bad (between 0.6 and 1.7 points for an experienced operator), the standard deviation of reproducibility is poor (1 to 5 points according to laboratories). That means that finding 10 points difference in results of the test for a same sample, on a 0-100 scale, is not aberrant. This can end, when the result is expressed in absorbance units, to a very high percentage of error (weak quality).

Furthermore, LASSERAN (1991) observes that, when the test indicates a bad quality, in a case on two, the sample presents a good wet-milling quality almost always confirmed by the test of sedimentation. Conversely, a sample found good by the test really is in 90% of cases.

In commercial transactions based on the turbidity test, the buyer seems to be therefore more favored than the salesman.

It is definitely a rapid test and not a fine chemical analysis.

1.2.5 Experimental protocol

The experimental protocol is adapted from the method used by NELLIST and BRUCE at AFRC, in England, for the study of the germination viability degradation and the baking quality of the wheat during its drying.

The experimental principle is schematized on the figure 1.4. Sachets in thin plastic are filled with a thin layer of approximately 60 g of whole corn grains with known moisture content X and quality Q_0 (result of the turbidity test expressed in absorbance units). Sachets are then vacuum sealed, immersed in a bain-marie water bath (controlled temperature) during a duration t . One cools the sachet when it

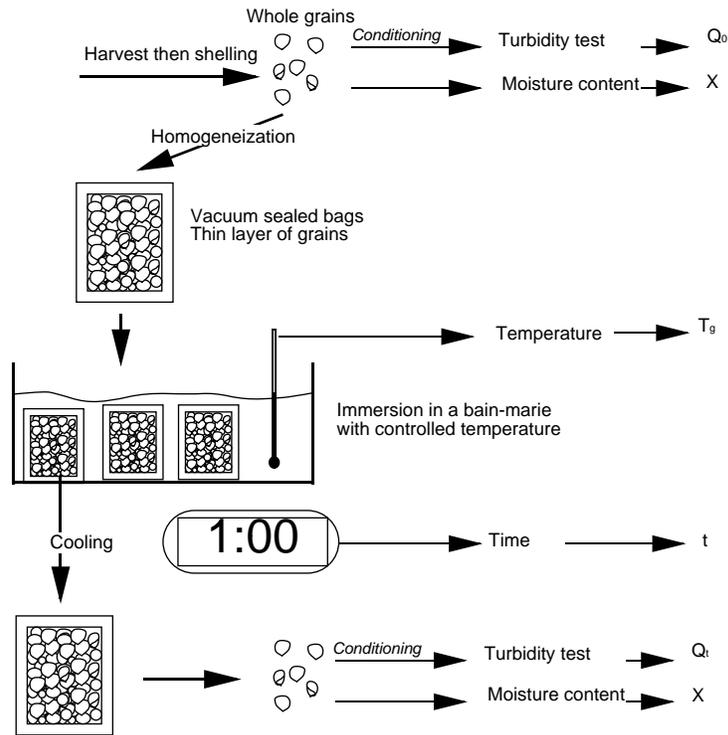


Figure 1.4: Principle of an experiment.

exits from the bain-marie then one conditions the grain to a moisture content close to 0.17 (necessary for the analysis) before to measure its quality Q_t .

The moisture content X of the grain is measured, in fact, before and after the immersion so as to verify the absence of drying during the experience.

An experiment with a thermocouple placed at the center of a grain, itself situated at the center of the sachet, has allowed to observe the thermal equilibrium of the grain in less than 5 minutes despite the presence of air in the sachet (bad tightness caused by the passage of the thermocouple in the sachet). We have therefore assimilated, by the continuation, the temperature T_g of the grain to that of the bain-marie.

In collaboration with the statistical service of the ITCF, we had anticipated to use 3 sachets for each curve point: just compromise between diminution of noises (experimental, natural) and limitation of the number of experiments. In fact, seeing the overload of work, we have done it only for some curve, during the exploratory phase .

1.2.6 Numerical methods

The parameter adjustment has been realized with an algorithm combining successively methods:

- ALIENOR (CHERRUAULT, 1986),
- Hooke & Jeeves (LEBERT, 1991),
- Simple (LEBERT, 1991).

1.3 Experimental study

1.3.1 Study of the time parameter

By immersing, in the bain-marie, so much sachets that from desired experimental points and by pulling them each at a given time, one can plot the corn degradation kinetic given the temperature. One has thus represented the kinetics to low and high temperatures (figures 1.5 and 1.6). One observes that for the absorbance inferior to 0.05 (i.e. 95% of transmission) the experimental curve is very noisy and of difficult interpretation. This is probably due to the spectrophotometric measure.

In fact, this quality domain $[0, 0.05]$ represents very damaged grains that the test is known to be unable to discriminate. It does not present therefore practical interest.

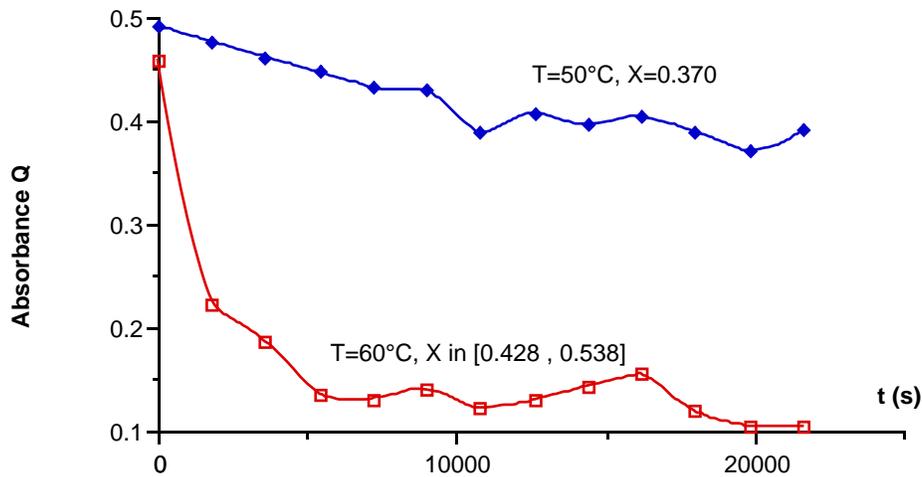


Figure 1.5: quality degradation kinetics at low temperature. At 60°C, the moisture content of the corn is not uniform on all the curve.

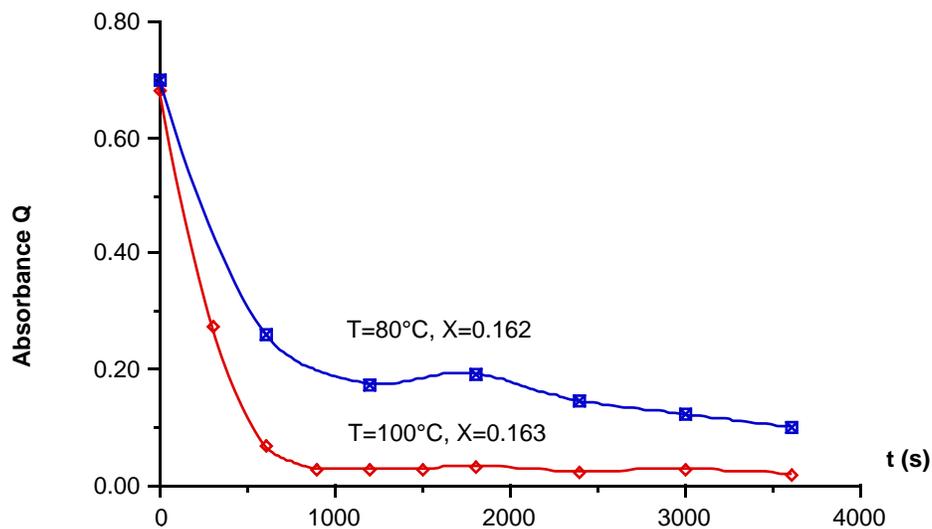


Figure 1.6: quality degradation kinetics at high temperature.

1.3.2 Study of the temperature parameter

The only a priori knowledge on the subject is that the more the grain is hot the more it is damaged. By using a homogeneous corn sample immersed in bains-marie of different temperatures, one obtains the curve of the figure 1.7. The sigmoid shape expresses two facts:

- so that the temperature of the grain remains inferior to 50°C, the degradation remains imperceptible to the scale of a drying time,
- Above 100°C, problems of practical order prevent to observe differences of quality.

Measures on industrial dryers led by the ITCF have shown that the temperature of grains, in the course of their drying, varies essentially between 50 and 70°C, sensitive zone of the curve. It appears therefore clearly that even small errors in the estimation of the grain temperature reverberate strongly in the quality prediction.

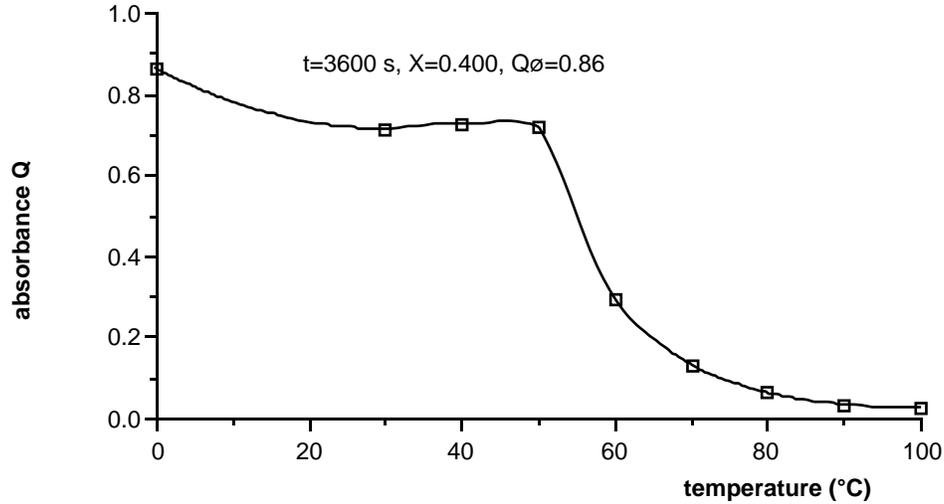


Figure 1.7: Influence of the temperature of the bath on the final quality of the corn after 1 hour of immersion.

1.3.3 Study of the moisture content parameter

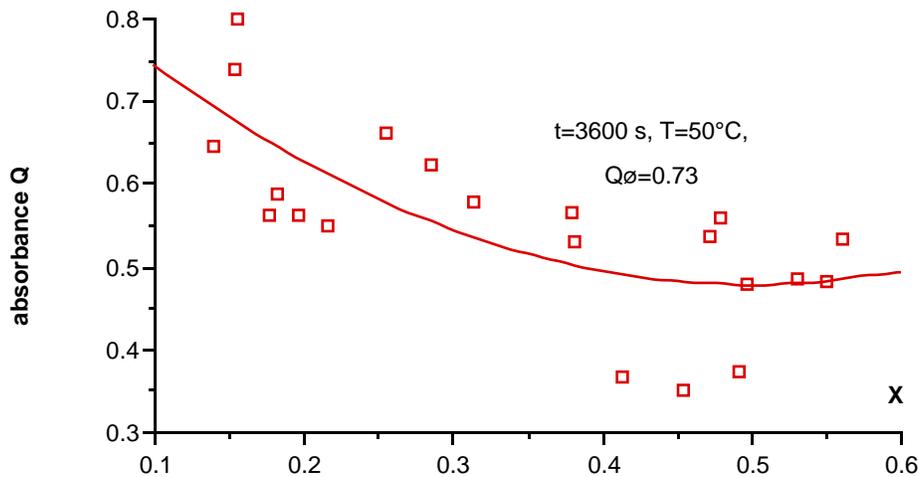


Figure 1.8: Influence of the moisture content of grains on the final quality of the corn after 1 hour of immersion to 50°C.

By conditioning a homogeneous corn share to several moisture contents and by immersing each corresponding sachets in a same bain-marie during one hour, one obtains curves of figures 1.8 and 1.9. One notices that they present both a parabolic shape without anyone being able to confirm the presence of an extremum at 0.5 kg of water by kg of dry matter.

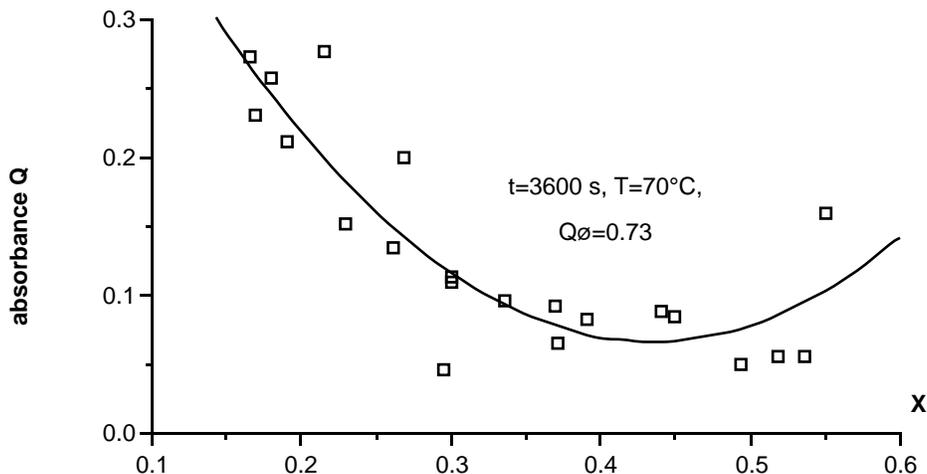


Figure 1.9: Influence of the moisture content of grains on the final quality of the corn after 1 hour of immersion at 70°C.

In fact, during the two years of this study, the dryness has prevented to study the degradation of very humid corn. Moreover it is practically impossible to have a rewetted corn at a moisture content higher than 0.6 without being roof in surface.

1.3.4 Combined study of parameters

From preceding results, so as to allow a numerical adjustment of the model, a series of experimentations has been realized to cover in the best possible manner the functioning domain of dryers. Due to many practical and climatical (especially) constraints, no experimental design could be used.

On the figure 1.10 that regroups a hundred of experiences, one finds results of 2 preceding effects, in a combined manner. This graph represents the influence of the temperature of the bath T and the moisture content of grains X on their final quality Q_f after immersion of 1 hour (Q_0 variable according to experiments). It appears clearly that Q_f is all the more low that temperature and moisture content are high.

1.4 Model adjustment, simulations

We pose the following assumptions:

- phenomena relative to the degradation of the quality are identical, at least qualitatively, that there is drying or not,
- the degradation of the wet-milling quality is assumed to be a unique chemical reaction with an integer order,
- the grain moisture content is constant in the course of the experiment,
- the time of the grain heating in the beginning of the immersion is negligible (constant T_g in the course the experiment and equal to the controlled temperature of the bath),

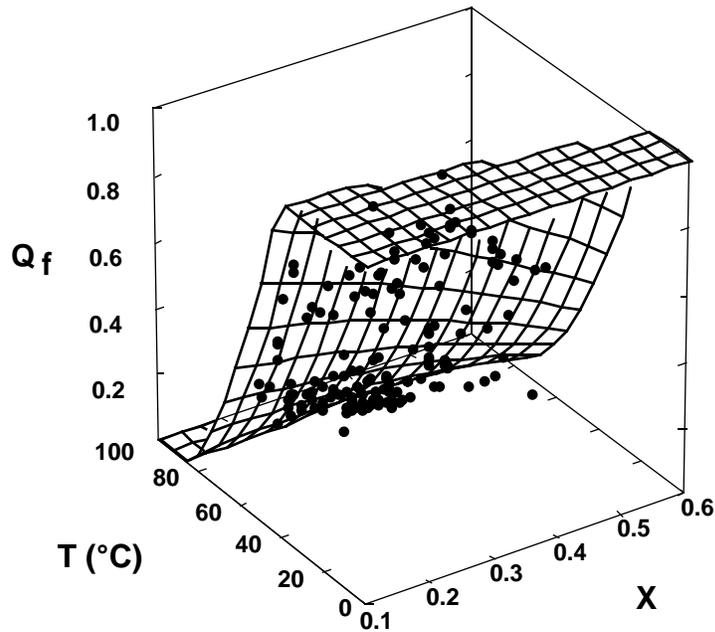


Figure 1.10: Influence of the moisture content of grains and the temperature of the bath on the final quality of the corn after 1 hour of immersion.

- the time of the grain cooling at the end of immersion is negligible (no degradation),
- experimental sachets are homogeneous and uniform in temperature, moisture content and quality (each grain is identical to others),
- corn samples are homogeneous and uniform in temperature, moisture content and quality (null variability).

The first point couldn't be studied experimentally but will be verified numerically in next chapters. It is the last point, added to the test uncertainties, that is the most disputable: after harvesting, the moisture content of grains can vary from more of 10 points of humidity (up to 50% of the average moisture content), the initial quality can also vary from approximately 10%. Moreover, the water is not distributed evenly in the grain, its maturity is variable and therefore its biochemical characteristics also.

To have the best possible adjustment, in spite of these problems, experiments have been multiplied.

So as to determine n , the kinetic order, the curves:

- $\text{Log}(Q)$ function of t (order 1),
- Q^{-1} function to t (order 2),
- Q^{-2} function to t (order 3),

have been plotted for each kinetic file (Q expressed in absorbance units). It appeared clearly (figures 1.11 and 1.12) that it is the curve Q^{-1} function of t (reaction of order 2) that is the most linear.

The kinetic is therefore of order 2 because by deriving:

$$\frac{1}{Q} = K_Q \cdot t + \text{constant}$$

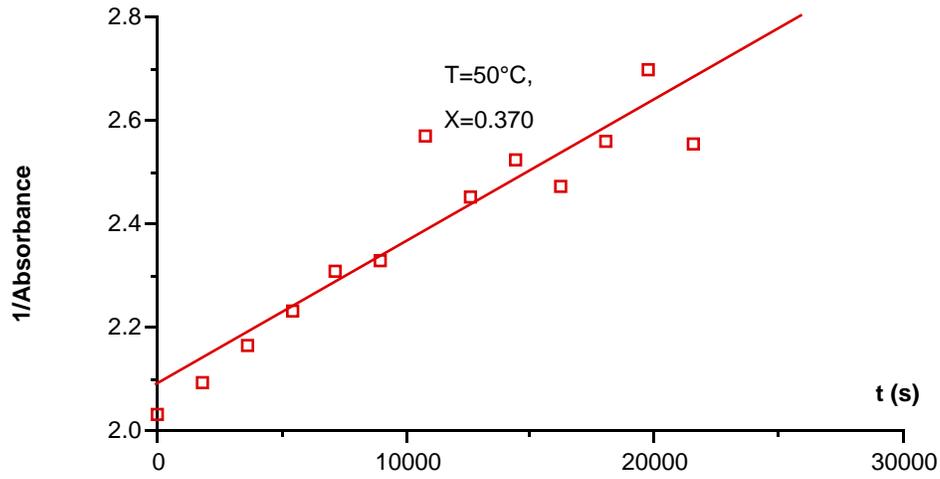


Figure 1.11: Linearization of a kinetic at 50°C (order 2).

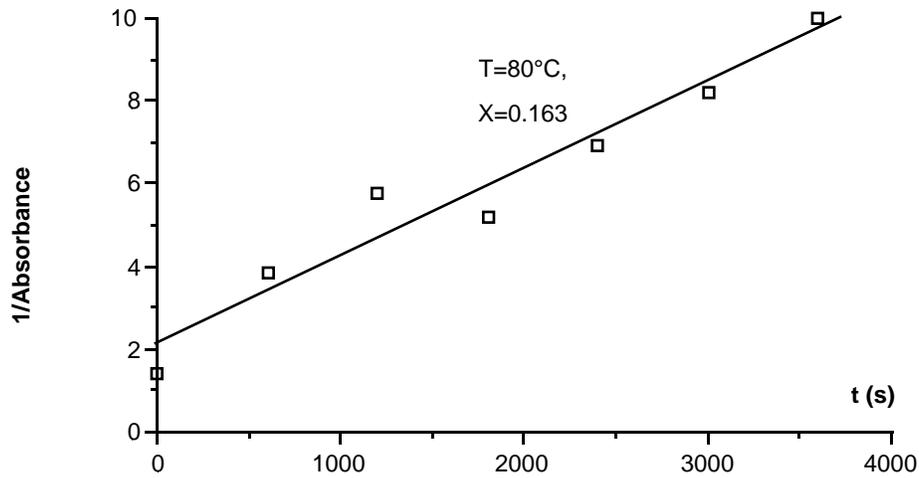


Figure 1.12: Linearization of a kinetic at 80°C (order 2).

one obtains :

$$\frac{\delta Q}{\delta t} = -K_Q \cdot Q^2 \quad (1.2)$$

Knowing the kinetic order, one calculates, for each experiment, the apparent coefficient K_Q , according to the equation:

$$K_Q = \frac{\frac{1}{Q_f} - \frac{1}{Q_0}}{t} \quad (1.3)$$

One observes that K_Q varies with operative conditions and more particularly with the temperature (figure 1.13).

An Arrhenius law is used to render this dependency :

$$K_Q = K_{Q0} \cdot e^{\frac{E_a}{R \cdot (T_g + 273.16)}} \quad (1.4)$$

with

$$K_{Q0} = -1.9561 \cdot 10^{16} + 5.4287 \cdot 10^{17} \cdot X + 6.8210 \cdot 10^{17} \cdot X^2 \quad (1.5)$$

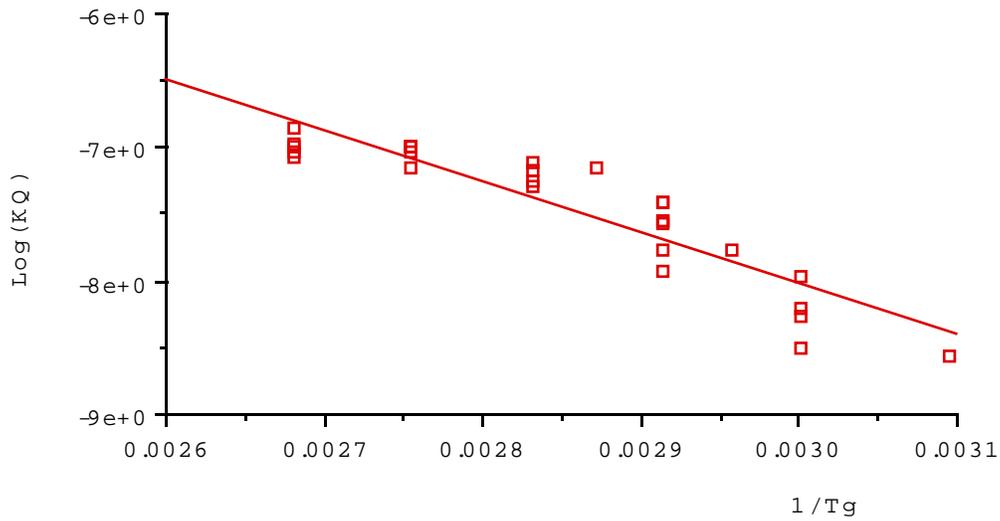


Figure 1.13: Relationship between K_Q and temperature (in Kelvin here).

$$E_a = -133.2 \cdot 10^3 \text{ J.mol}^{-1} \quad (1.6)$$

Numerical parameter values of equations (1.5) and (1.6) have been determined with the help of a numerical adjustment operated on autumn 1989 experiments (462 data). The method consists of a combination of ALIENOR, SIMPLEX and HOOKE & JEEVES algorithms.

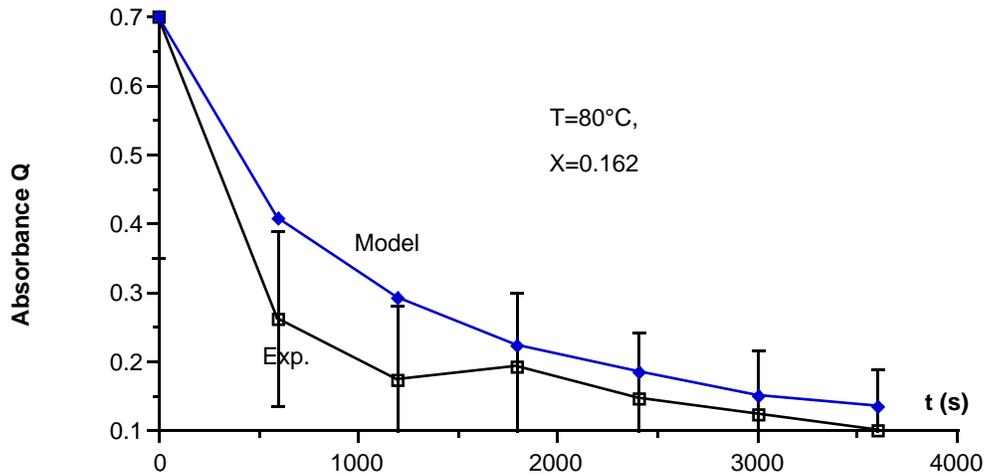


Figure 1.14: Comparison between experimental and calculated kinetics with bars of measure uncertainty. The uncertainty is calculated from a value of 7 points, on the value expressed in % of transmission, then converted in absorbance units.

The opposite step consisting in to compare the final quality of an experiment with the calculation gives an error less than 10 points of transmission for 75% of data of the adjustment (campaign 89), with an average error of 7.5 points. On experimental data of the campaign 1990 (not used for the adjustment), the average error is decreased down to 5.5 points of transmission. Curves of the figure 1.14 give an idea of the average precision of the simulation compared to the high uncertainty on experimental results.

Results concerning drying experiences will be discussed in next chapters.

1.5 Conclusion

Despite two years of dryness, preventing to have a very humid corn and shortening the study, many results have been obtained. These data already represent a qualitative basis of non negligible practical interest for the design and setting of industrial dryers. Met precision problems have already been improved partly during the second campaign of experimentation by acquisition of a know-how. Nevertheless one can expect a best numerical adjustment of the model by replacing the turbidity test, badly adapted to the modelling, by the PROMATEST whose development is in progress at ITCF. This test is especially based on a measure of light intensity with a spectrophotometer, directly in absorbance units, whose correspondence is easy with an equivalent albumin concentration.

The result of this study is a dynamic balance equation (or model of quality degradation) easy to insert in any corn drying model. But according to the acuteness of the grain temperature simulation, a loss of precision is to fear in the range 60-80°C (grain temperature) so that a readjustment can be useful.

Chapter 2

Modelling of the thin layer drying

2.1 Bibliography

The thin layer, basis of the drying model, is nevertheless independent of the dryer's technology; it is specific to the dried product.

Due to this specificity, many food and agricultural products have been studied (BIMBENET *et al.*, 1984). For a same product, the variety, the crop age and type etc. have also their importance on its behavior (LEVESQUE *et al.*, 1986; STROSHINE and MARTINS, 1986).

The thin layer is, from its definition (DAUDIN, 1982), a layer of sufficiently small product's thickness in order that one could consider that air characteristics (V_a , T_a , Y) everywhere in the layer are identical. This implies the absence of any gradient between grains and therefore, in our case, the equivalence between grains.

Finally, the study of the thin layer drying is equivalent to the study of an "average grain" drying.

2.1.1 Flows and forces

There exists two drying principles : convective and boiling (BIMBENET, 1984). Corn dryers are of convective drying type, with an air that serves both as a heat vector (it brings necessary calories for the heating of grains) and a gas vector (it evacuates the humidity of the grain).

Some authors have tried to show, through experimentation or with the help of the theory (WHITAKER, 1988), phenomena that intervene in the course the drying. But, and it is one of the great difficulties for scientists, each product reacts differently to the drying, and particularly in a complex manner in the case of biological products. The diversity of experimental drying curves and the abundant literature that illustrates it (BIMBENET *et al.*, 1984), is a flawless example.

DAUDIN (1982) made a review of the phenomena happening in the course of the drying. Globally one observes:

- a growing moisture content gradient to the center of the product,
- a growing temperature gradient to the surface of the product.

To these phenomena, one can add pressure, partial vapor pressure and superficial tension gradients...even then, taking in account the migration of the solutes and its influence on that of the water (BIMBENET *et al.*, 1970) or the influence of the gravity (PUIGGALI *et al.*, 1988).

More, these gradients impose a mechanical stress or tensor of constraints that ends generally by a modification of the product volume and shape (LITCHFIELD and OKOS, 1988; CHEN, 1973) and therefore of some quality criteria.

A difficulty resides in the quasi-impossibility to quantify the influence of each of these gradients. ABID *et al.* (1988) have shown, in the case of the corn grain drying in fluidized-bed, by a sensitivity study on the coefficient of temperature-driven water migration in their model (simplified TPI approach), that this heat-dependent diffusion was negligible compared to the moisture-driven diffusion of the water.

Most of authors simplifies their model assuming the water migrates in the liquid form by diffusion and evaporates at the surface, while the heat is transferred by conduction at the interior of the grain.

2.1.2 Air / grain transfers

For a long time, and for computation reasons, one has considered the grain as a homogeneous unit, with no internal gradient. The classic approach consisted in writing mass and heat balances in the grain, then to substitute to $\delta X/\delta t$ an empirical function of t, T_a, Y and V_a obtained from thin layer experiments. It is the case of DAUDIN (1982) who has sought the most judicious transformation so as to regroup all kinetics in one single curve.

But FOHR *et al.* (1988) have shown the limits of this type of approach in the case of sharp variation of the air characteristic in entry, general case in industrial dryers where the grain changes of level and therefore drying conditions approximately every minutes !

This approach has nevertheless permitted to improve the knowledge of the influence of the different drying parameters : especially the essential importance of the air temperature T_a (ABID *et al.*, 1988; DAUDIN, 1982) that influences all along the drying duration, through the influence on T_g (temperature of the grain), on the transfer constants in the grain. Parameters V_a and Y (air velocity and moisture content), remain external factors and influence essentially the drying beginning at the moment where air / grain transfers constitute the limiting factor.

From thin layer experimentations, it has been found a great number of empirical laws used in models to describe the transfer of water between the grain and the air (SOKHANSANJ and CENKOWSKI, 1988; DAUDIN, 1982).

One can nevertheless summarize them as follows:

- laws giving the moisture content of the grain as a function of the time

$$X = f(t, T_a, Y, V_a)$$

the function is generally an exponential ; this type of law is dedicated to the thin layer drying in constant conditions and is no longer practically used for the modelling,

- laws giving the variation of moisture content of the grain as a function of the time

$$\frac{\delta X}{\delta t} = f(t, T_a, Y, V_a)$$

they are defined for a given product and surface area, they fit only in constant condition drying (steady state) and render difficultly possible rewettings, except through global mass balances (BAKKER ARKEMA *et al.*, 1974; WILSON and NGUYEN, 1988),

- laws giving the variation of moisture content of the grain as a function of the distance to equilibrium

$$\frac{\delta X}{\delta t} = Coefficient.(X - X_{eq})$$

with $X_{eq} = f(T_a, Y, V_a)$ and $Coefficient = f(T_a, Y, V_a)$ these are powerful laws that can render directly rewettings and, possibly, unsteady states.

A more "physical" version is given by the law of mass transfer between 2 phases (LONCIN, 1985):

$$\frac{\delta X}{\delta t} = \beta_p \cdot A_g \cdot (P_v - P_{va}) \text{ with } P_v = Aw \cdot P_{v_{sat}}$$

what seems more logical since water is transferred in the gaseous form.

2.1.3 The interior of the grain

Thin layer experiments have allowed to increase the knowledge on the drying of biological products, especially by showing the existence of a "memory" or inertia (LAGUERRE *et al.*, 1989) that one can observe in the course of a drying experiment with a sudden change (temperature of the air changing brutally from a setpoint to an other).

Similarly, many authors (LASSERAN, 1989 a; ABID *et al.*, 1988) have observed experimentally, with the help of micro-thermocouples that the temperature gradient existing between the grain center and surface became negligible after a few minutes. Nevertheless, seeing the difficulty to measure the center temperature without creating a thermal shortcut, one can discuss the validity of this result. Anyway, it is a basic hypothesis for many scientists.

To simulate correctly unsteady states and, especially, "the memory effect" that one observes during periods of relaxation or jumps, it is appeared necessary to consider grain internal gradients.

One can regroup retained methods as followed :

- diffusive models where the grain is assimilated as a known shape (sphere or finite cylinder, generally), supposed homogeneous and isotropic,
 - a priori solved with infinite series by CRANK (1967), supposing constant the diffusivity and the moisture content at the surface (INGRAM, 1976; SILVA and NEBRA, 1988), they are limited to steady states ; one can note the attempt of NISHIYAMA (1987) to add, to the solution of the diffusion equation, a term allowing to render a tempering period but the demonstration and results are insufficiently clarified;
 - solved with the finite difference method (HAGHIGHI and SEGERLIND, 1988b; PATIL, 1988), they render well unsteady states but necessitate an important mesh and therefore a very bad calculation time to simulate a whole dryer.
- models from the TPI theory, more or less simplified. The great interest of these methods is that they allow to consider cross relationships between the different flows. Unfortunately most applications are based on inert materials (sand especially) far away from the products that concern us. Nevertheless, with many simplifications, sometimes simplifying them to become a simple diffusive/ convective model, one can find examples for corn : FORTES and OKOS (1982) have tried to simulate the dryeration (tempering then slow cooling in cell) by this method taking into account liquid water, vapor and heat flows but their model presents a great number of constants whose determination does not seem simple; ABID *et al.* (1988) add only the temperature-driven diffusion of the water to the classical diffusive / convective model to, finally, observe that it is negligible.
- "pseudo-physical" models, or considered as such, because they use laws derived from well established physical laws. It concerns essentially simple compartmental models (few compartments) broadly used in biology (CHERRUAULT, 1983). They present the huge interest to need small computations while simulating grain gradients, in a simplistic manner to be honest. A particularly interesting example is the model of TOYODA (1988) that represents a grain of rice as 2 concentric compartments or 2 tanks in cascade for the humidity (and a single compartment for the temperature) and finds that the water flow between 2 tanks is proportional to the moisture content difference between these

2 tanks. This model seems sufficient to simulate its recirculation dryer that alternates drying and tempering periods. At the ENSIA, LAGUERRE *et al.* (1989) have applied a similar compartmental approach for the modelling of the thin layer drying for other food products.

Hence, we have chosen to use a 3-compartments model only for the moisture content (uniform temperature). The peripheral compartment is the place of the water vaporization and the moisture content gradient is simulated essentially by the two other internal compartments.

2.1.4 Corn physical constants

A lot of authors forget to fully mention the constant used for their model. We consider fundamental to recognize the importance of constants on a model results, particularly when they are functions of several parameters.

Transfer coefficients

Transfer coefficient of heat α and matter β_p are linked by the relationship:

$$\frac{\alpha}{\beta_p \cdot L_v} = 64.7 \text{ Pa} \cdot \text{K}^{-1}$$

that is obtained from the COLBURN analogy (LONCIN AND MERSON, 1979).

It suffices therefore to determine α . RATTANAPANT (1986) has observed the great diversity of results obtained from empirical correlations on heat transfer, to finally prefer an experimental adjustment. One will be able nevertheless to note that BROOKER *et al.* (1974) use a value of α between 28 and 34 $\text{W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$ for the corn.

The density of dry product

KUPPINGER (1980) gives for the INRA 258 corn:

$$\rho_g = 1353 - 179.4 \cdot X + 78.4 \cdot X^2 \text{ with } 0.05 \leq X \leq 0.85$$

MHLBAUER (1974) gives, for the INRA 258 corn:

$$\rho_g = 1397 - 204 \cdot X \text{ with } 0.0 \leq X \leq 0.6$$

PABIS and HENDERSON (1962) give an average value of 1280 $\text{kg} \cdot \text{m}^{-3}$ without any precisions. It seems therefore that one can retain an average value of 1350 $\text{kg} \cdot \text{m}^{-3}$ that one will consider constant in the course of the drying.

The specific heat, at constant pressure, of dry product

BROOKER *et al.* (1974) as well as KAZARIAN and HALL (1963) give $c_{pg} = 1122 \text{ J} \cdot \text{kg}^{-1} \cdot \text{K}^{-1}$ for the "yellow dent corn". One will retain therefore this value.

The water activity of corn

$A_w = f(X, T_g)$ that depends on the variety considered.

One will be able to take the formula of THOMSON *et al.* (1968):

$$A_w = 1 - \exp[-0.6876 \cdot (T_g + 45.5555) \cdot X^2]$$

for the dent corn (figure 2.1).

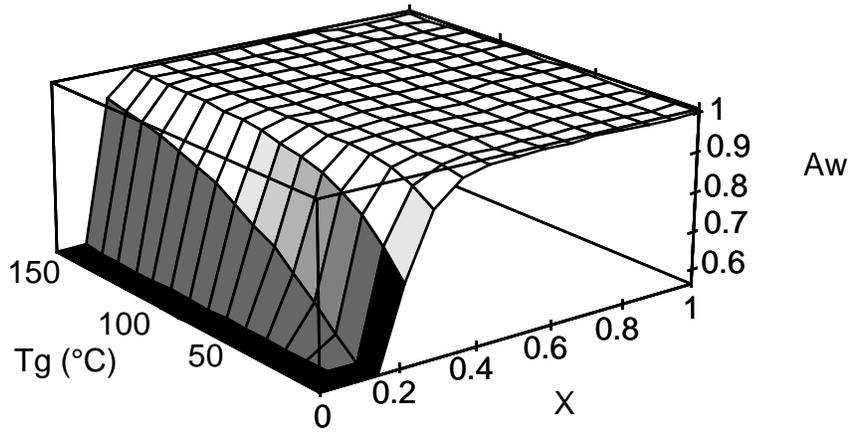


Figure 2.1: A_w function of X and T_g .

The bed porosity

$\epsilon = f(X)$ that depends very strongly on the variety and the moisture content. KUPPINGER (1980) gives for the corn INRA 258:

$$\epsilon = 0.513 - 0.11.X + 0.48.X^2 - 0.56.X^3 \text{ with } 0.05 \leq X \leq 0.85$$

MHLBAUER (1974) gives, for the corn INRA 258:

$$\epsilon = 0.390 + 0.095.X \text{ with } 0.1 \leq X \leq 0.6$$

THOMSON and ISAACS (1968) give an average value of 0.423 without any further precisions. In the meantime of an experimental determination, one will take 0.45.

The grain surface area / volume ratio

$a = \frac{A_g}{V_g} = f(X)$ that depends probably also on the variety.

BROOKER *et al.* (1974) give a value of 784.12 m^{-1} without any precisions. MHLBAUER (1974) gives for the INRA 258 corn, assimilating the grain as a sphere:

$$a = 0.003597.\pi.(7.28 + 0.236.X)^2.1350 \text{ with } 0.1 \leq X \leq 0.6$$

that gives 837 m^{-1} for $X = 0.538$ (35% of humidity).

One will be able to retain $a = 800 \text{ m}^{-1}$, as a constant, in the meantime of an experimental determination by the method recommended by LE MAGUER (1989). One should note that few authors specify the value of this fundamental parameter.

2.2 Material, methods

Since we had already experimental drying kinetics in thin layer and in constant conditions (DAUDIN, 1982), we have oriented essentially towards experiments in variable conditions. This way, we could adjust the model on kinetics in constant conditions and validate it in variable conditions.

2.2.1 Preparation of the samples

For our jumps and stop drying experiments, it has been necessary to rewet some corn samples. It has been provided by the laboratory of A. LE BRAS at the ITCF: it concerns harvested corn, on the same fields close to Etampes, in 1987 and 1988, dried during approximately 5 month in *cribs* (in cob, to open sky) and whose quality, except its moisture content, is very close to that of a freshly harvested grain.

Two methods of rewetting were used :

- soaking in water at ambient temperature during 24 h then drained at fresh air during 2 to 24 h.
- the method of DAUDIN (1982) that consists in leaving the corn soaking in the distilled water in jars placed in a cold bedroom during 15 days. The corn is then drained and stocked under plastic bags during 24 h in a refrigerator. An hour before the experiment, the product is displayed to the ambient air.

Some fresh corn, from the same origin, has been used for the experiments in 1989.

2.2.2 Experimental dryer

The dryer used was of the INRA-GIA's associated laboratory at the ENSIA (figure 2.2). The air conditioning device and its instrumentation have been deeply modified since 1988. Only the heating device, manually set then automatically controlled, has been used. The acquisition is centralized on the computer connected to the data acquisition unit.

This type of dryer presents three disadvantages:

- due to the fact of the discontinuous weighing device, the beginning of a kinetic is either poorly known, or well known but strongly influenced by the measure,
- it is impossible to pull the product in the course of an experiment without influencing the kinetic, what prevents to plot a kinetic of drying coupled to a kinetic of degradation of the wet-milling quality,
- it is impossible to work below 0.5 m.s^{-1} for the input air velocity : this prevents to experiment in the correct range of industrial drying conditions.

2.2.3 EULER method

It is a simple method of numerical integration for ordinary differential equation (ODE) systems (SI-BONY and MARDON, 1982). In our case, with a system of 5 coupled differential equations, with 5 independent variables (X_1, X_2, X_3, T_g, Q), it is necessary to make the hypothesis that the chosen step size for the time-integration will be sufficiently small in order that variables could be considered independent during the duration of an iteration. In practice, we have verified that EULER and RUNGE KUTTA (fourth order) methods gave exactly the same result, with a comparable numerical stability. This led us to retain the EULER method as the simplest and, by far, the most rapid one.

To avoid numerical divergence problems, an adaptive set size method has been developed : one calculates Δt at the beginning of each iteration according to

$$\Delta t = \frac{0.05}{\text{Maximum}\left\{\frac{\delta X_1}{\delta t} \cdot \frac{1}{X_1}, \frac{\delta X_2}{\delta t} \cdot \frac{1}{X_2}, \frac{\delta X_3}{\delta t} \cdot \frac{1}{X_3}, \frac{\delta T_g}{\delta t} \cdot \frac{1}{T_g}\right\}}$$

This method limits relative variations of each variable to 5% maximum in the course of an iteration and allows to prevent practically all numerical divergence. Moreover, the simulation is far more rapid.

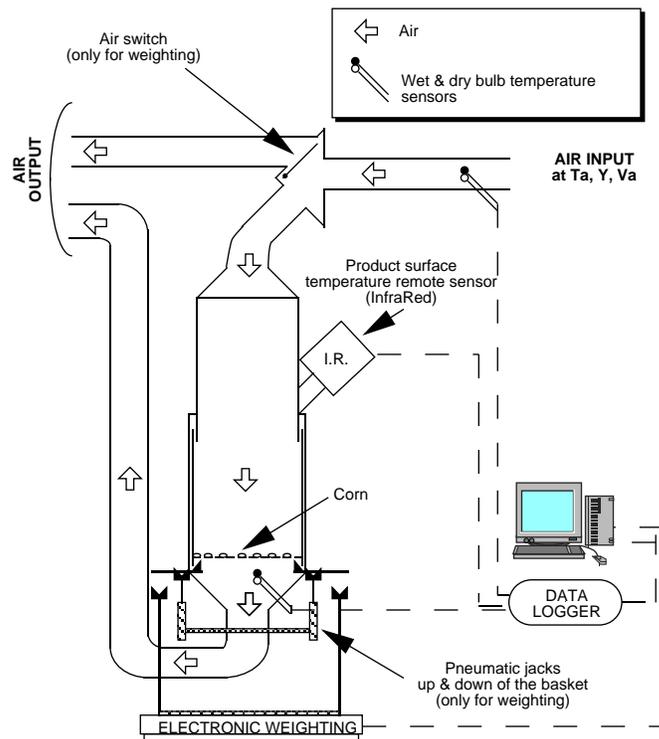


Figure 2.2: Experimental Dryer INRA-GIA.

2.2.4 SIMPLEX method

It concerns a method of non linear optimization that allows to identify the model parameters by adjusting the simulation to the experiments. Several variants exist, but we have used that of ALLANEAU (1979) which allows a rapid adaptation of the SIMPLEX by spatial conformation changes at each iteration.

Two minimization criteria have been successively used:

- sum of squares of the grain moisture content differences, between simulated and experimental points divided by the square of the experimental value,
- approximation of the surface between simulated and experimental curves, by the trapezium method.

The commonly used criterion of the sum of squares of differences has not been retained because it favored the adjustment on the first part of the drying where the moisture content of the grain is higher. The first chosen criterion, more performing, has however the defect to be dependent on the number of experimental points and is thus valid only when experimental points are regularly spaced. This is why, the second criterion has been preferred for stops and jumps of drying. Simulations on computer being suitable in simple precision, the criterion of stop of the SIMPLEX was a standard deviation between all its summits inferior to 10^{-6} for the first criterion and 10^{-6} times the desired criterion value in the other case.

2.3 Model description

The grain is supposed uniform in temperature and each of its compartment in moisture content. The compartment 3 is considered as the place of the water vaporization and its possible condensation (figure 2.3).

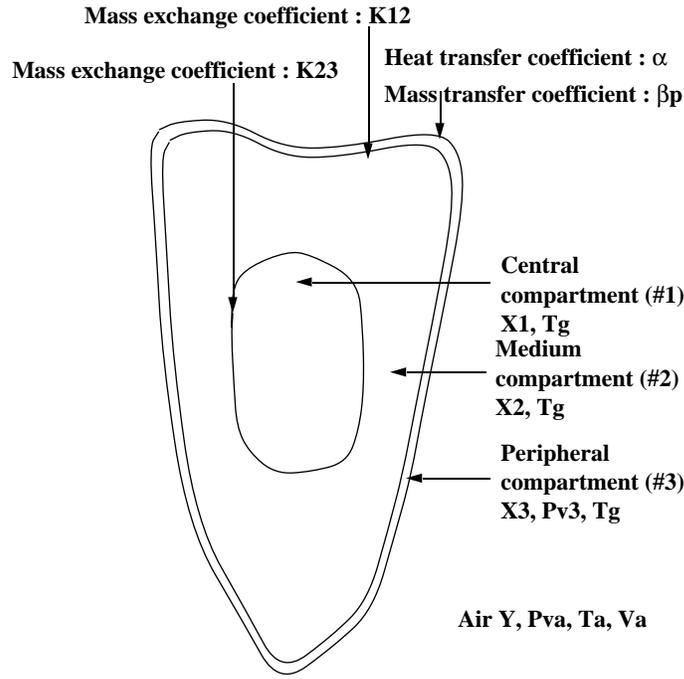


Figure 2.3: representation of an "average grain".

The only geometric hypothesis concerns each compartment proportions as compared to the totality of the grain: the compartment 3 is arbitrarily assumed to be 10% of the total volume, 45% for each others.

In the case of a thin layer, taking into account mass and heat transfers between a grain and the surrounding air, one has the following flow densities (LONCIN, 1985; BIMBENET, 1984):

$$\Phi_m = \beta_p \cdot (P_{v3} - P_{va}) \text{ with } P_{v3} = Aw \cdot P_{vsat} \quad (2.1)$$

$$\Phi_c = \alpha \cdot (T_g - T_a) \quad (2.2)$$

and, by analogy, one puts, for water flows between internal compartments (TOYODA, 1988):

$$D_{12} = K_{12} \cdot (X_1 - X_2) \quad (2.3)$$

$$D_{23} = K_{23} \cdot (X_2 - X_3) \quad (2.4)$$

one can therefore write water balances in the grain (we assume all grains are identical):

$$\begin{aligned} &\text{variation of the water mass of the compartment } i \\ &= \\ &\text{water flow from the compartment } i - 1 \\ &- \\ &\text{water flow to the compartment } i + 1 \end{aligned}$$

are, for compartments 1, 2 and 3:

$$\frac{\delta(\rho_g \cdot V_g \cdot \tau_1 \cdot X_1)}{\delta t} = -D_{12} \quad (2.5)$$

$$\frac{\delta(\rho_g \cdot V_g \cdot \tau_2 \cdot X_2)}{\delta t} = D_{12} - D_{23} \quad (2.6)$$

$$\frac{\delta(\rho_g \cdot V_g \cdot \tau_3 \cdot X_3)}{\delta t} = D_{23} - A_g \cdot \Phi_m \quad (2.7)$$

We assume:

- water vaporization occurs only in the compartment 3;

and, to simplify the calculation:

- one neglects terms corresponding to partial derivatives of ρ_g , τ_i , V_g (no variation of the grain shape).

what gives, finally:

$$\frac{\delta X_1}{\delta t} = \frac{-D_{12}}{\rho_g \cdot V_g \cdot \tau_1} = \frac{B_1}{\rho_g \cdot \tau_1} \cdot (X_2 - X_1) \quad (2.8)$$

with $B_1 = \frac{K_{12}}{V_g}$ in $kg \cdot s^{-1} \cdot m^{-3}$

$$\frac{\delta X_2}{\delta t} = \frac{D_{12} - D_{23}}{\rho_g \cdot V_g \cdot \tau_2} = \frac{B_1}{\rho_g \cdot \tau_2} \cdot (X_1 - X_2) + \frac{B_2}{\rho_g \cdot \tau_2} \cdot (X_3 - X_2) \quad (2.9)$$

with $B_2 = \frac{K_{23}}{V_g}$ in $kg \cdot s^{-1} \cdot m^{-3}$

$$\frac{\delta X_3}{\delta t} = \frac{D_{23} - A_g \cdot \Phi_m}{\rho_g \cdot V_g \cdot \tau_3} = \frac{B_2}{\rho_g \cdot \tau_3} \cdot (X_2 - X_3) + \frac{\beta_p \cdot a}{\rho_g \cdot \tau_3} \cdot (P_{va} - P_{v3}) \quad (2.10)$$

then, by posing $X = \tau_1 \cdot X_1 + \tau_2 \cdot X_2 + \tau_3 \cdot X_3$ that represents the average moisture content of the grain, we obtain

$$\frac{\delta X}{\delta t} = \frac{A_g \cdot \Phi_m}{\rho_g \cdot V_g} = \frac{\beta_p \cdot a}{\rho_g} \cdot (P_{va} - P_{v3}) \quad (2.11)$$

and for the temperature, in the case of a positive Φ_m (drying):

$$\begin{aligned} & \text{speed of variation of the volumic energy load} \\ & = \\ & \text{speed of volumic energy production} \end{aligned}$$

thus:

$$\frac{\delta(\rho_g \cdot (c_{pg} + X \cdot c_{pw}) \cdot T_g)}{\delta t} = -a \cdot \Phi_c - a \cdot \Phi_m \cdot (H_v + c_{pw} \cdot T_g) \quad (2.12)$$

Hypothesis: one neglects the variation of c_{pw} and c_{pg} with T_g .

This gives:

$$\frac{\delta T_g}{\delta t} = -a \cdot \frac{\Phi_c + \Phi_m \cdot L_v}{\rho_g \cdot (c_{pg} + X \cdot c_{pw})} = \frac{-\alpha \cdot a \cdot (T_g - T_a) - \beta_p \cdot a \cdot (P_{va} - P_{v3}) \cdot L_v}{\rho_g \cdot (c_{pg} + X \cdot c_{pw})} \quad (2.13)$$

and in the case of a negative Φ_m (rewetting):

$$\frac{\delta T_g}{\delta t} = -a \cdot \frac{\Phi_c + \Phi_m \cdot [T_a \cdot c_{pv} - T_g \cdot c_{pw} + L_v]}{\rho_g \cdot (c_{pg} + X \cdot c_{pw})} = \frac{-\alpha \cdot a \cdot (T_g - T_a) - \beta_p \cdot a \cdot (P_{va} - P_{v3}) \cdot [T_a \cdot c_{pv} - T_g \cdot c_{pw} + L_v]}{\rho_g \cdot (c_{pg} + X \cdot c_{pw})} \quad (2.14)$$

Furthermore, one can add the supplementary equation relative to the degradation of the corn wet-milling quality (*cf.* chapter 1):

$$\frac{\delta Q}{\delta t} = -K_Q \cdot Q^2 \quad (2.15)$$

To simulate the thin layer drying of the corn, it is necessary therefore to solve the following system :

$$\frac{\delta X_1}{\delta t} = \frac{B_1}{\rho_g \cdot \tau_1} \cdot (X_2 - X_1)$$

$$\frac{\delta X_2}{\delta t} = \frac{B_1}{\rho_g \cdot \tau_2} \cdot (X_1 - X_2) + \frac{B_2}{\rho_g \cdot \tau_2} \cdot (X_3 - X_2)$$

$$\frac{\delta X_3}{\delta t} = \frac{B_2}{\rho_g \cdot \tau_3} \cdot (X_2 - X_3) + \frac{\beta_p \cdot a}{\rho_g \cdot \tau_3} \cdot (P_{va} - P_{v3})$$

$$\frac{\delta Q}{\delta t} = -K_Q \cdot Q^2$$

$$\frac{\delta T_g}{\delta t} = \frac{-\alpha \cdot a \cdot (T_g - T_a) - \beta_p \cdot a \cdot (P_{va} - P_{v3}) \cdot L_v}{\rho_g \cdot (c_{pg} + X \cdot c_{pw})}$$

K_Q has been determined in chapter 1,
 τ_1 , τ_2 and τ_3 have been fixed arbitrarily, and
 α , B_1 and B_2 are adjusted with DAUDIN's experimentations (1982).

2.4 Results

2.4.1 Drying in constant conditions

The study of the model in constant conditions is based on kinetic files from DAUDIN (1982) noted MAIS5.CIN to MAIS34.CIN. These data have the disadvantage not to cover the entire drying domain of an industrial dryer for air velocity and especially not to be distributed according to an experimental design. For the grain initial conditions, in a simplifying purpose, one writes $X_1 = X_2 = X_3 = X = X_0 =$ moisture content at the time 0 in the file and, for the temperature one takes $T_g = 20^\circ C$.

A first adjustment on the experimental file MAIS5.CIN ($T_a = 56^\circ C$, $Y = 0.011$ and $V_{ahc} = 2 \text{ m.s}^{-1}$) has been necessary to center our sensitivity study on values of α , B_1 and B_2 . This study has shown that the choice of Δt , time step size in EULER method, was limited essentially by T_a (60 s at $50^\circ C$, 5 s at $100^\circ C$) to avoid numerical instability leading to a divergence.

From these observations, a method with an adaptive time step size has been developed, improving both stability and rapidity.

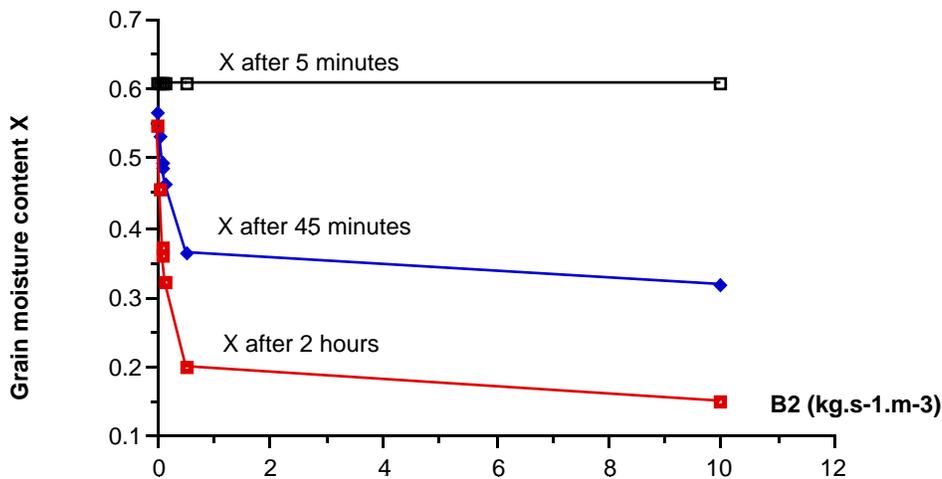


Figure 2.4: Influence of the coefficient B_2 on the grain moisture content X in the case of a simulation centered on the MAIS5.CIN experiment ($T_a = 56^\circ C$, $Y = 0.011$ and $V_{ahc} = 2 \text{ m.s}^{-1}$).

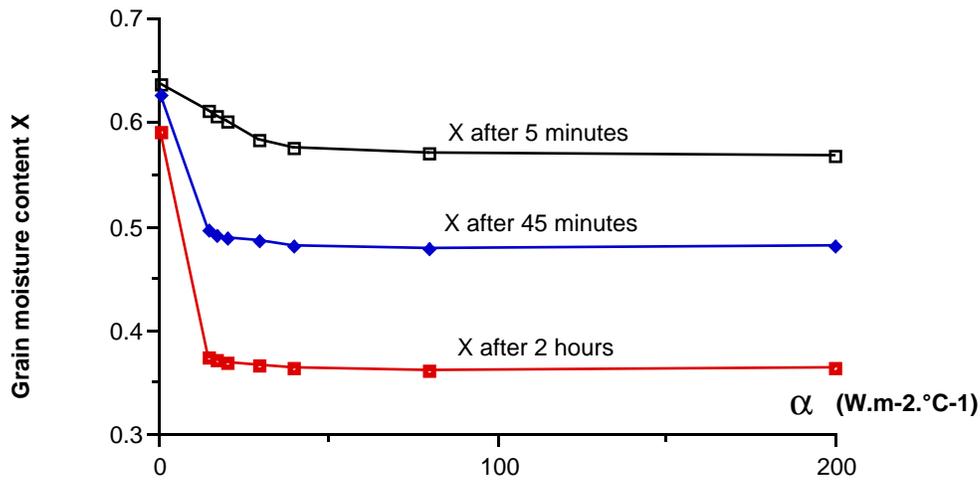


Figure 2.5: Influence of the coefficient α on the grain moisture content X in the case of a simulation centered on the MAIS5.CIN experiment ($T_a = 56^\circ\text{C}$, $Y = 0.011$ and $V_{ahc} = 2 \text{ m.s}^{-1}$).

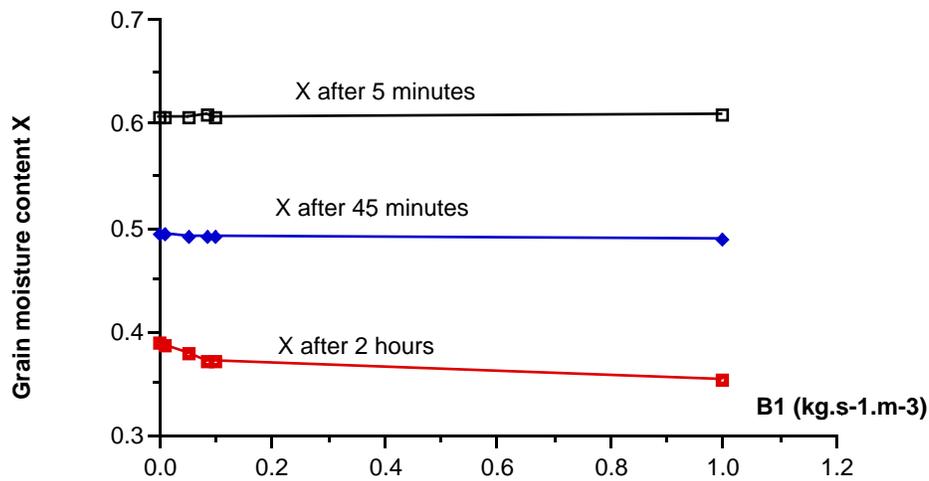


Figure 2.6: Influence of the coefficient B_1 on the grain moisture content X in the case of a simulation centered on the MAIS5.CIN experiment ($T_a = 56^\circ\text{C}$, $Y = 0.011$ and $V_{ahc} = 2 \text{ m.s}^{-1}$).

This same study, generalized to different drying conditions, has shown:

- the major importance of the coefficient B_2 on the simulation (figure 2.4, B_2 is inferior to $1 \text{ kg.s}^{-1}.\text{m}^{-3}$),
- that α is of little influence, after 5 minutes, over a threshold value near $20 - 30 \text{ W.m}^{-2}.\text{K}^{-1}$ (figure 2.5),
- that B_1 is practically of no influence in the course of the first 2 hours (figure 2.6) because, under 100°C , the compartment 1 dries only very slowly (figure 2.7).

In fact the model is built in such manner that the limiting factor is successively α (during first 5 minutes approximately), then B_2 (during a time depending very strongly on T_a) and finally B_1 at the end of drying.

The SIMPLEX method has been used to adjust the model parameters α , B_1 and B_2 to each DAUDIN's experimental kinetics (table 2.1).

Table 2.1: Experimental files of DAUDIN (1982) and results of adjustments.

MSDOS file	T_a ($^{\circ}C$)	Y	V_{ahc} (m/s)	B_1 ($kg.s^{-1}.m^{-3}$)	B_2 ($kg.s^{-1}.m^{-3}$)	α ($W.m^{-2}.K^{-1}$)
MAIS5.CIN	56	0.011	2	0.086	0.103	17.4
MAIS6.CIN	109	0.011	2	0.135	0.9431	66.26
MAIS7.CIN	56	0.011	0.7	0.112	0.0918	8.4
MAIS8.CIN	59	0.01	2.5	0.149	0.09	13.03
MAIS9.CIN	106	0.012	1.5	0.112	0.868	60.9
MAIS10.CIN	106	0.01	2.5	0.132	0.855	65.02
MAIS11.CIN	106	0.012	0.7	0.105	0.708	40.28
MAIS12.CIN	115	0.016	1.5	0.142	0.892	38.2
MAIS13.CIN	75	0.01	1.5	0.043	0.213	9.1
MAIS14.CIN	91	0.012	1.5	0.058	0.474	26.98
MAIS15.CIN	40	0.01	1.5	0.153	0.029	5.52
MAIS16.CIN	65	0.012	1.5	0.03	0.119	13.68
MAIS17.CIN	125	0.018	1.5	0.145	1.29	28.1
MAIS18.CIN	49	0.007	1.5	0.046	0.0549	7.94
MAIS19.CIN	56	0.011	1.5	0.04	0.0816	10.36
MAIS20.CIN	57	0.055	0.7	0.03	0.0874	17.88
MAIS21.CIN	40	0.03	1.5	0.026	0.0317	25.34
MAIS22.CIN	56	0.023	1.5	0.072	0.0923	18.66
MAIS23.CIN	56	0.045	1.5	0.063	0.116	19.13
MAIS24.CIN	56	0.07	1.5	0.007	0.1369	16.79
MAIS25.CIN	76	0.03	1.5	0.057	0.241	25.22
MAIS26.CIN	76	0.055	1.5	0.144	0.343	43.88
MAIS27.CIN	106	0.028	1.5	0.114	0.6298	53.73
MAIS28.CIN	107	0.092	1.5	0.175	1.03	58.41
MAIS29.CIN	57	0.069	2.5	0.015	0.0987	18.24
MAIS30.CIN	137	0.018	1.5	0.228	1.51	37.52
MAIS31.CIN	150	0.013	1.7	0.662	4.86	45.13
MAIS32.CIN	76	0.097	1.5	0.05	0.189	87.6
MAIS34.CIN	106	0.04	1.5	0.174	1.094	86.98

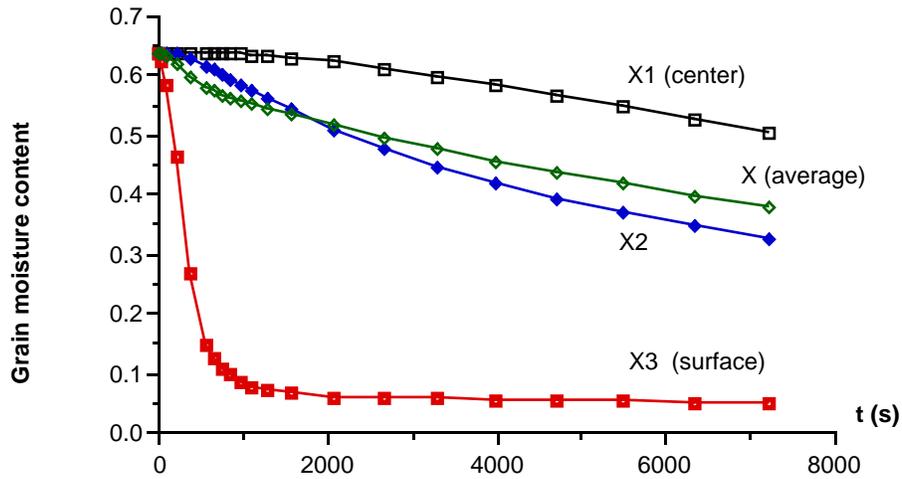


Figure 2.7: Profile of grain moisture content in the case of a simulation adjusted on the MAIS5.CIN experiment ($T_a = 56^\circ C$, $Y = 0.011$ and $V_{ahc} = 2 \text{ m.s}^{-1}$).

From this study, different informations have been extracted:

- it is not possible to correlate simply α with experimental conditions, particularly with V_{ahc} , but this is due to both the design of the experimental dryer and the "experimental design" used by DAUDIN, limiting studied air velocities,
- except the high temperature experiments (137 and $150^\circ C$) or longer than 4 hours, B_1 is not a limiting factor on these kinetics and stay well centered around an average value of $0.1 \text{ kg.s}^{-1}.\text{m}^{-3}$,
- one can plot an exponential regression between B_2 and T_a with a correlation coefficient close to 0.96 (figure 2.8).

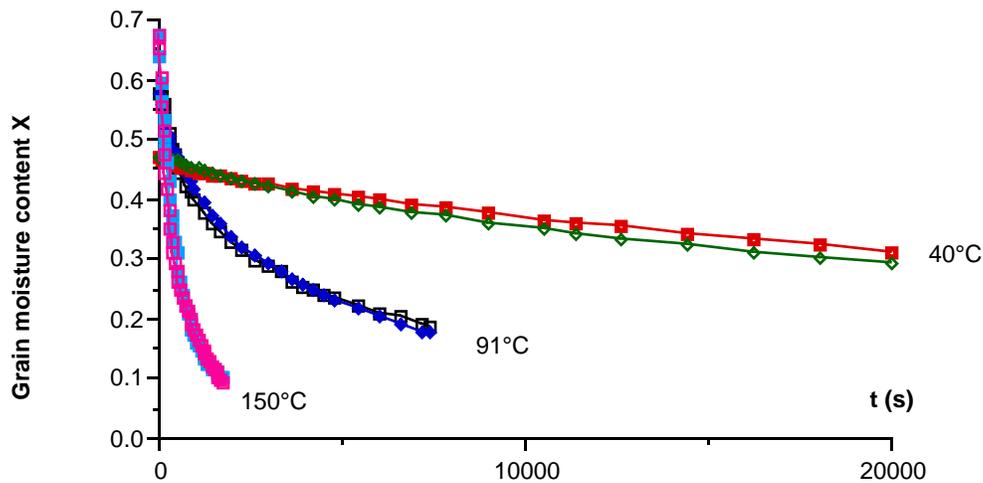


Figure 2.8: Exponential curve fitting relating the coefficient B_2 to the air temperature T_a based on adjustments relative to DAUDIN's experiments (1982).

To improve the quality of the simulation, from DAUDIN's long or high temperature experiments plus some experiments of very long duration that we have realized at different temperatures, the SIMPLEX method has allowed the following adjustment:

$$B_1 = \exp[-5.521 + 0.0335.T_g]$$

Similarly, since it has not been possible to have a good correlation between α and V_{ahc} , a multiple linear regression on T_a and Y has allowed to explain 60% of its variability:

$$\alpha = -19.72 + 0.5152.T_a + 379.Y$$

Finally with the following 3 adjustments:

$$B_1 = \exp[-5.521 + 0.0335.T_g]$$

$$B_2 = \exp[-4.753 + 0.0421.T_a]$$

$$\alpha = -19.72 + 0.5152.T_a + 379.Y$$

we have obtained a model capable to simulate all DAUDIN's experiments and all of our experiments (figure 2.9) including condensates sometime met at the beginning (figure 2.10).

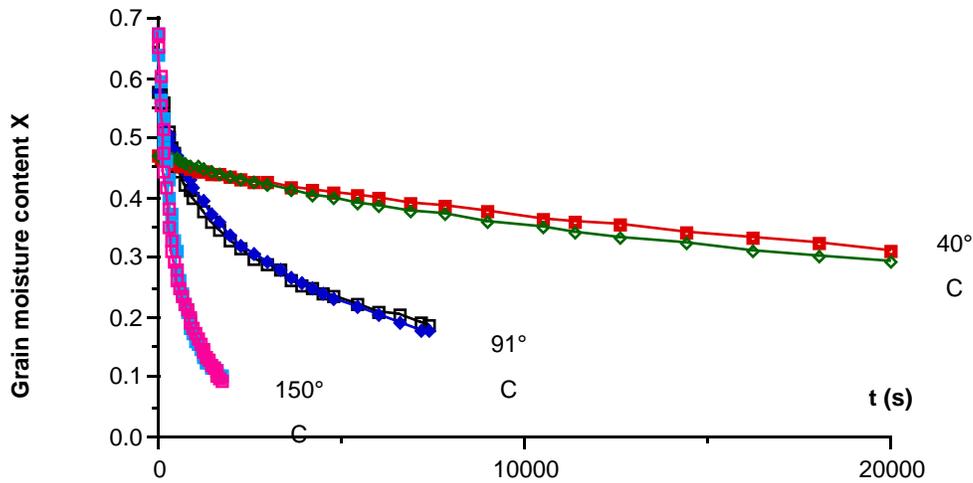


Figure 2.9: Comparison between 3 recent experimental curves and curves calculated with the model adjusted on DAUDIN (1982).

2.4.2 Drying in variable conditions

Cooling experiments have shown obviously the influence of experimental problems on the interpretation of drying kinetics in variable conditions. The grain is heated, in a hermetic bag placed in an oven, then it is introduced in the experimental dryer where circulates an air at 30°C .

But, it is practically impossible to heat beforehand the grain without drying it. This point, added to the fact that B_2 is connected to T_a and not to T_g gives a simulation that underestimates a bit the drying in the course of the cooling.

Similarly, the thermal inertia of the totality of the experimental system (important metallic mass of the dryer) in the course of a jump of air temperature renders difficult a precise quantitative interpretation of the kinetics.

A first series of experiments of drying stops has been realized by exiting the basket at ambient temperature and by covering it with a plastic. But this first method does not allow to manage correctly

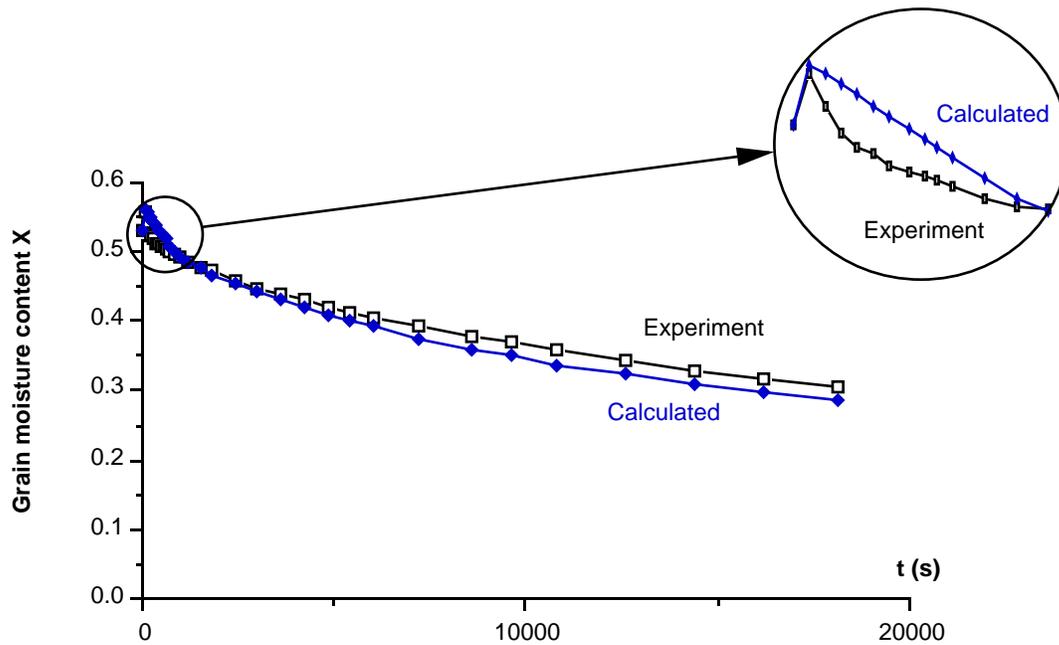


Figure 2.10: Comparison between an experimental curve with rewetting and the curve calculated with the model ($T_a = 56^\circ C$, $Y = 0.070$ and $V_{ahc} = 1.5 \text{ m}\cdot\text{s}^{-1}$).

the temperature factor and one observes always an undesirable residual drying during the tempering. The corresponding simulation is realized from the model adjusted in constant conditions, by writing $\beta_p = 0$ and $T_a = 20^\circ C$ during the tempering period.

Following these tests, it has been necessary to revise the protocol:

- 1 to 4 hours have seemed necessary to obtain a significant re-equilibration of the corn grain,
- in the course of the stop, the corn has to be placed in a supple plastic, hermetic, without air, in a steamer at the same temperature than the drying air : for the model, it suffices then to write $\beta_p = 0$ (and therefore $\alpha = 0$).

In fact, this last type of experiment has appeared to us, by far, being the most reliable and the easiest to master.

On the figure 2.11, one can observe a good agreement between experimental and simulated curves in the case of an one hour stop. It is necessary, indeed, to compare the weak gap between 2 curves with the various experimental uncertainties and with the accumulation of rounding errors in the course of the simulation. More, the gap becomes significant only after a duration of eight drying hours, very superior to the average residence time in an industrial dryer.

It is necessary to note that B_1 plays here an important role since it controls, with B_2 , the re-equilibration of moisture content that one observes during stops. This diminution of the moisture content gradient inside the grain allows a resumption of the drying at a higher drying rate (figures 2.12 and 2.13).

2.4.3 Drying and quality degradation

A series of thin layer drying experiments has been realized with the fresh corn of the ITCF on which one has measured the wet-milling quality before and after the experiment thanks to the "test of turbidity" expressed in absorbance units.

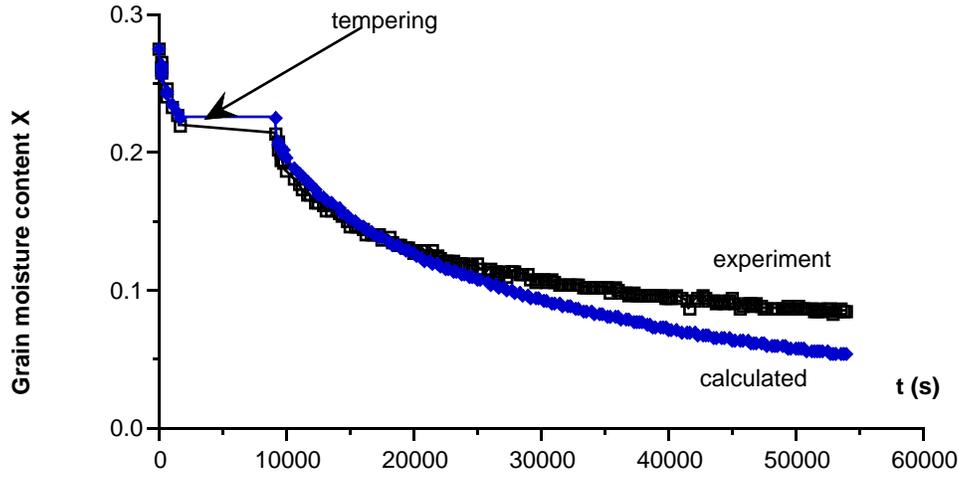


Figure 2.11: Comparison between one of our experimental curves ($T_a = 60^\circ C$, $Y = 0.005$ and $V_{ahc} = 1.8 \text{ m.s}^{-1}$) with stop of 2 drying hours at $60^\circ C$, and the curve calculated with the model adjusted on DAUDIN (1982).

The figure 2.14 shows a good agreement between measured and simulated qualities compared to the measure uncertainty. But especially, the general shape of the relationship $Q_f = f(T_a)$ is identical to that observed in the case of a thermal shock at constant moisture content (*cf.* chapter 1).

2.5 Conclusion

This model is able to simulate all types of thin layer drying of corn (or any other type of grain) : constant, variable, with stop, with jump, with condensation.

The quality comes to be added as a quantity whose one writes the instantaneous balance, according to the same method that for the heat, on a small interval of time dt . Corresponding equations have been determined experimentally in chapter 1.

It is thus possible to design the tempering stages of industrial dryer, or tempering cells between 2 dryers in series, to obtain the most complete re-equilibration of the grain moisture content and limiting the degradation of the wet-milling quality.

To improve again the precision of simulations, several ways may be interesting:

- An experimental fluidized bed dryer would allow to obtain a both more physical and finer correlation of α with drying air characteristics and of K_Q with T_g and X .
- A general re-adjustment, on all DAUDIN's kinetics as well as on our long duration kinetics, to identify simultaneously τ_i and B_2 coefficients, would allow to connect B_2 to T_g instead of T_a .

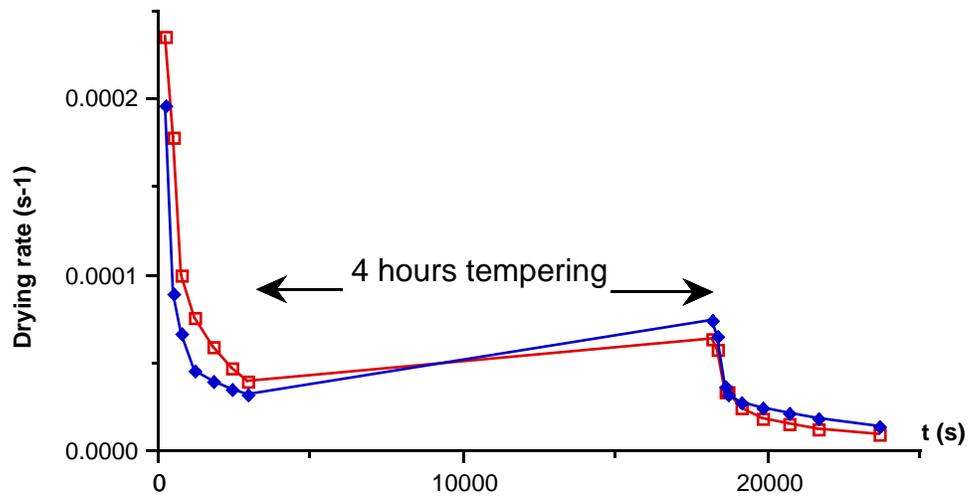


Figure 2.12: Comparison between one of our experimental curves ($T_a = 61^\circ C$, $Y = 0.010$ and $V_{ahc} = 1.8 \text{ m.s}^{-1}$) with 4 hours stop of drying at $60^\circ C$, and the curve calculated with the model adjusted on DAUDIN (1982). The experimental drying rate is calculated with a moving second-order polynomial.

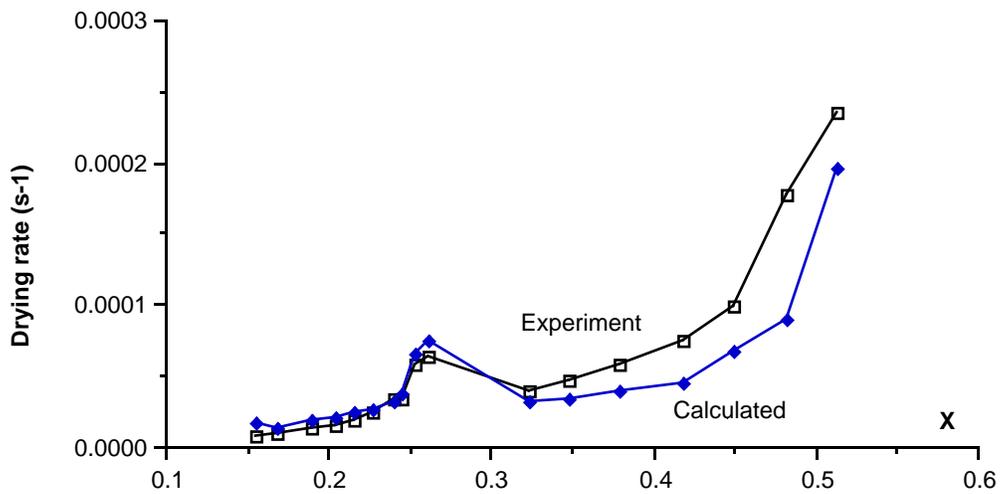


Figure 2.13: Comparison between one of our experimental curves ($T_a = 61^\circ C$, $Y = 0.010$, $V_{ahc} = 1.8 \text{ m.s}^{-1}$) with 4 hours stop of drying at $60^\circ C$, and the curve calculated with the model adjusted on DAUDIN (1982). The experimental drying speed is calculated with a moving second-order polynomial.

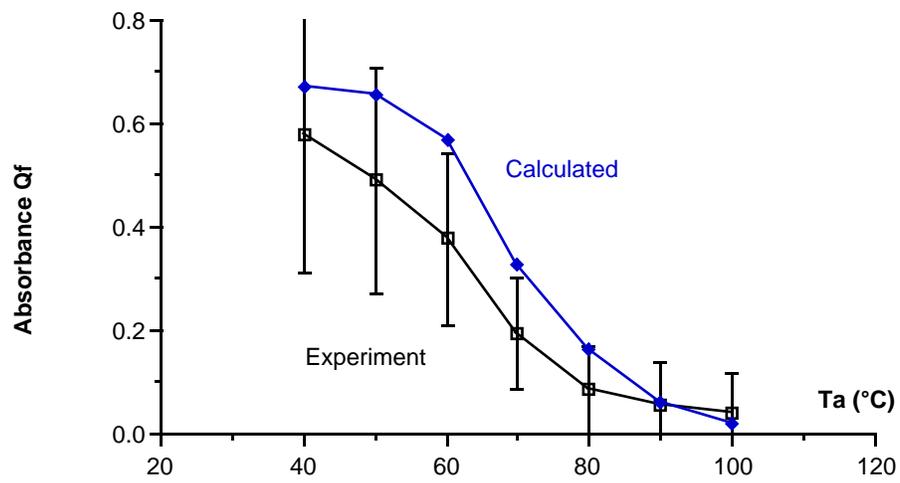


Figure 2.14: Comparison between measured final qualities, for some of our drying experiments ($t = 3600\text{ s}$, $Y = 0.005$ and $V_{ahc} = 1.8\text{ m.s}^{-1}$, $Q = 0.673$) at different air temperatures, and qualities predicted by the model.

Chapter 3

Modelling of the deep bed drying

The "deep bed" step in the dryer modelling has a triple interest :

- to validate the "thin layer" model,
- to develop a method, well-suited, for the numerical resolution of the system, in the space and time,
- to study the evolution of the air variables in the course of the drying.

Thus, it concerns to develop the elementary part that one will combine to construct the industrial dryer simulator.

3.1 Bibliography, equations, assumptions

Looking at the deep bed brings a supplementary dimension as compared to the thin layer: space. Indeed, one can no longer neglect the evolution of the air characteristics in the course of its going through the deep bed of grains. We need now to account for these air moisture content and temperature gradients; and this with a "dynamic" point of view.

One can consider that, in the literature, two types of methods exist :

- The resolution in finite elements (ARNAUD and FOHR, 1991) presents the interest to take into account complex air-flow problems, grain to grain conduction, compression and even grain shrinkage. Indeed, one writes equations of transfers for practically each grain of the deep bed (according to the mesh grid and a possibly symmetry). This type of calculation is very long on computer and is therefore limited, by these authors, to the study and to the design of air ducts of dryer. However, the power increase of computer calculation may allow, in the future, to generalize this type of method to a whole dryer.
- The formal decomposition of the deep bed in a succession of thin layers (figure 3.1) uses the symmetry around the axis materialized by the air trajectory. This method, that supposes a plug-type air flow, is not well-suited to study the influence of a complex air flow on the drying. On the other hand, the calculation time is far more weak and conditioned essentially by the thickness of grain bed. It is the most used method, so at the ENSIA (DAUDIN, 1982; TECHASENA RATTANAPANT, 1989), even in the world (BRUCE, 1983; BAKKER ARKEMA *et al.*, 1974).

This last method has appeared to us being the most adapted to our purpose: to simulate a corn industrial dryer in steady state and in unsteady state.

Necessary supplementary assumptions for the application of the "thin layer" model presented in chapter 2, according to this method, are:

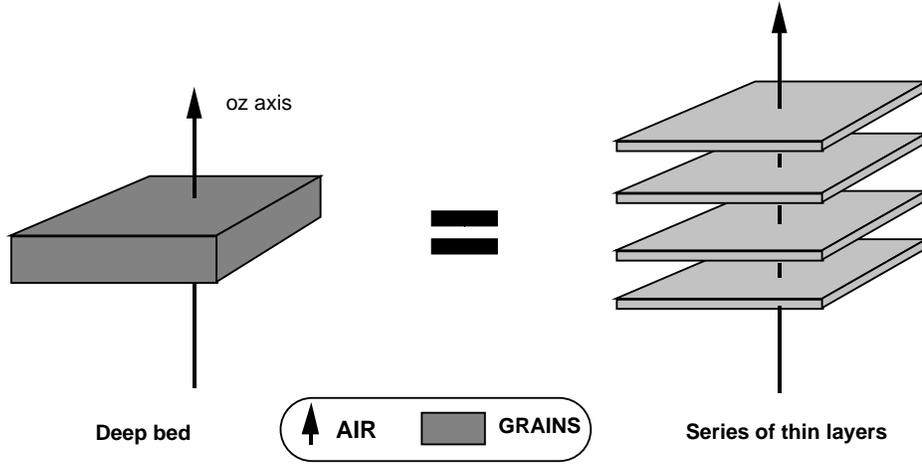


Figure 3.1: Potential decomposition of a deep bed in a succession of thin layer.

- plug-type air flow with no preferential path,
- negligible pressure loss (constant and uniform P),
- no "grain to grain" direct transfers on the oz axis,
- no compression in the grain bed (constant and uniform ϵ),
- negligible "grain to grain" surface area (a same as in chapter 2),

We have therefore assimilated the deep bed as a series of thin layers whose only transfers are between air and grains.

Transfer balances in the air, taking into account the volume of dryer $S.dz$ and more particularly the volume occupied by the air $\epsilon.S.dz$ (DAUDIN, 1982), can be written as :

$$\begin{aligned} & \text{speed of variation of the volumic load of energy} \\ & = \\ & \quad - \text{div}[\text{energy flow density}] \\ & \quad + \text{speed of volumic production of energy} \end{aligned}$$

one can therefore write for the **water balance in the air** :

$$\frac{\delta(\rho_a \cdot Y)}{\delta t} = -\text{div}(V_a \cdot \rho_a \cdot Y) + \Phi_m \cdot a \cdot \frac{(1 - \epsilon)}{\epsilon} \quad (3.1)$$

with $V_a = V_{ahc}/\epsilon$

hypothesis: one supposes that there is no local air accumulation (constant ρ_a).

what gives:

$$\frac{\delta Y}{\delta t} = -V_a \cdot \frac{\delta Y}{\delta z} + \Phi_m \cdot a \cdot \frac{(1 - \epsilon)}{\rho_a \cdot \epsilon} \quad (3.2)$$

and for the heat balance, in the case of a positive Φ_m (drying):

$$\frac{\delta(\rho_a \cdot (c_{pa} + Y \cdot c_{pv}) \cdot T_a)}{\delta t} = -\text{div}[V_a \cdot \rho_a \cdot (c_{pa} + Y \cdot c_{pv}) \cdot T_a] + a \cdot \frac{(1 - \epsilon)}{\epsilon} \cdot [\Phi_m \cdot H_v + \Phi_c] \quad (3.3)$$

hypothesis: one neglects the variation of c_{pv} and c_{pa} with T_a .

what gives:

$$\frac{\delta T_a}{\delta t} = -V_a \cdot \frac{\delta T_a}{\delta z} + a \cdot \frac{(1-\epsilon)}{\epsilon} \cdot \frac{\Phi_m \cdot c_{pv} \cdot (T_g - T_a) + \Phi_c}{\rho_a \cdot (c_{pa} + Y \cdot c_{pv})} \quad (3.4)$$

in the case of a negative Φ_m (rewetting):

$$\frac{\delta T_a}{\delta t} = -V_a \cdot \frac{\delta T_a}{\delta z} + a \cdot \frac{(1-\epsilon)}{\epsilon} \cdot \frac{\Phi_c}{\rho_a \cdot (c_{pa} + Y \cdot c_{pv})} \quad (3.5)$$

In LONCIN (1985), one finds constants relative to air and steam characteristics (at $P = 10^5$ Pa and $T_a = 100^\circ C$):

$$\begin{aligned} \rho_a &= 0.950 \text{ kg.m}^{-3} \\ c_{pa} &= 1012 \text{ J.kg}^{-1}.K^{-1} \\ c_{pw} &= 4210 \text{ J.kg}^{-1}.K^{-1} \\ c_{pv} &= 2030 \text{ J.kg}^{-1}.K^{-1} \\ L_v &= 2.357.10^6 \text{ J.kg}^{-1} \end{aligned}$$

that one will really use as constants (what is justified by their weak variation in the considered domain).

3.2 Numerical solution

Taking into account that the deep bed is a series of thin layers whose thickness is Δz (the oz axis is equal to the air trajectory with the same direction) and that the time step Δt is sufficiently small to consider that variables are independent on this interval, one can transform the equation 3.2 into :

$$\frac{Y(t + \Delta t, z) - Y(t, z)}{\Delta t} = -V_a \cdot \frac{Y(t + \Delta t, z + \Delta z) - Y(t + \Delta t, z - \Delta z)}{2 \cdot \Delta z} + \frac{a \cdot (1-\epsilon) \cdot \Phi_m(t, z)}{\epsilon \cdot \rho_a} \quad (3.6)$$

and, similarly, the equation 3.4 into :

$$\begin{aligned} \frac{T_a(t + \Delta t, z) - T_a(t, z)}{\Delta t} = & -V_a \cdot \frac{T_a(t + \Delta t, z + \Delta z) - T_a(t + \Delta t, z - \Delta z)}{2 \cdot \Delta z} \\ & + \frac{a \cdot (1-\epsilon)}{\epsilon \cdot \rho_a} \cdot \frac{\Phi_m(t, z) \cdot c_{pv} \cdot (T_g(t, z) - T_a(t, z)) + \Phi_c(t, z)}{c_{pa} + Y(t, z) \cdot c_{pv}} \end{aligned} \quad (3.7)$$

It is thus a method of implicit finite differences.

By separating terms in t and these $t + \Delta t$, one ends to the following vectorial notation :

$$[Y(t + \Delta t)] = MAT \cdot \left([Y(t)] + \frac{a \cdot (1-\epsilon) \cdot \Phi_m(t, z)}{\epsilon \cdot \rho_a} \right) \quad (3.8)$$

and

$$[T_a(t + \Delta t)] = MAT \cdot \left([T_a(t)] + \frac{a \cdot (1-\epsilon)}{\epsilon \cdot \rho_a} \cdot \frac{\Phi_m(t, z) \cdot c_{pv} \cdot (T_g(t, z) - T_a(t, z)) + \Phi_c(t, z)}{c_{pa} + Y(t, z) \cdot c_{pv}} \right) \quad (3.9)$$

where MAT is the reverse of the following squared matrix :

$$\begin{pmatrix} 1 - \frac{V_{ahc} \cdot \Delta t}{\epsilon \cdot \Delta z} & \frac{V_{ahc} \cdot \Delta t}{\epsilon \cdot \Delta z} & 0 & \dots & 0 \\ \frac{V_{ahc} \cdot \Delta t}{2 \cdot \epsilon \cdot \Delta z} & 1 & -\frac{V_{ahc} \cdot \Delta t}{2 \cdot \epsilon \cdot \Delta z} & \ddots & \vdots \\ 0 & \ddots & \ddots & \ddots & 0 \\ \vdots & \ddots & \frac{V_{ahc} \cdot \Delta t}{2 \cdot \epsilon \cdot \Delta z} & 1 & -\frac{V_{ahc} \cdot \Delta t}{2 \cdot \epsilon \cdot \Delta z} \\ 0 & \dots & 0 & -\frac{V_{ahc} \cdot \Delta t}{\epsilon \cdot \Delta z} & 1 + \frac{V_{ahc} \cdot \Delta t}{\epsilon \cdot \Delta z} \end{pmatrix}$$

It suffices therefore to recalculate, for each t , values of X_1, X_2, X_3, X, T_g, Q and the second term in the parenthesis of equations 3.8 and 3.9 for each thin layer with the help of equations from chapters 1 and 2, then Y and T_a with the help of equations 3.8 and 3.9.

Unfortunately, the step time Δt is limited to 0.01 s maximum without what the calculation diverges very rapidly. It is necessary to notice that the associated explicit method imposes a maximum time step of 0.0001 s. These values are maladjusted for the simulation, on a microcomputer, of a whole dryer.

We have therefore researched a faster method to solve the deep bed system.

By resuming to equations 3.2 and 3.4 and by making the following assumptions (DAUDIN, 1982):

$$\frac{\delta Y}{\delta t} \text{ is negligible compared to } -V_a \cdot \frac{\delta Y}{\delta z} \text{ and } \frac{a \cdot (1 - \epsilon) \cdot \Phi_m}{\epsilon \cdot \rho_a}$$

$$\frac{\delta T_a}{\delta t} \text{ is negligible compared to } -V_a \cdot \frac{\delta T_a}{\delta z} \text{ and } \frac{a \cdot (1 - \epsilon) \cdot \Phi_m \cdot c_{pv} \cdot (T_g - T_a) + \Phi_c}{\epsilon \cdot \rho_a + Y \cdot c_{pv}}$$

one then obtains the simplified equations :

$$\frac{\delta Y}{\delta z} = \frac{a \cdot (1 - \epsilon) \cdot \Phi_m}{V_a \cdot \epsilon \cdot \rho_a} \quad (3.10)$$

$$\frac{\delta T_a}{\delta z} = \frac{a \cdot (1 - \epsilon) \cdot \Phi_m \cdot c_{pv} \cdot (T_g - T_a) + \Phi_c}{\epsilon \cdot \rho_a + Y \cdot c_{pv}} \quad (3.11)$$

that one can write in the form of finite differences :

$$\frac{Y(t, z + \Delta z) - Y(t, z)}{\Delta z} = \frac{a \cdot (1 - \epsilon) \cdot \Phi_m(t, z)}{V_a \cdot \epsilon \cdot \rho_a} \quad (3.12)$$

$$\frac{T_a(t, z + \Delta z) - T_a(t, z)}{\Delta z} = \frac{a \cdot (1 - \epsilon) \cdot \Phi_m(t, z) \cdot c_{pv} \cdot (T_g(t, z) - T_a(t, z)) + \Phi_c(t, z)}{\epsilon \cdot \rho_a + Y(t, z) \cdot c_{pv}} \quad (3.13)$$

Having, by hypothesis, neglected instantaneous variations of Y and T_a compared to their variations in the space, one can suppose that Δt is sufficiently small in order that Y and T_a are constant on this interval.

Then one ends to a robust and simple method of variable integration in the space and time. At each sampling time Δt , one recalculates all the $Y(t, z)$ and $T_a(t, z)$ with the help of equations 3.12 and 3.13, one writes $Y(t + \Delta t, z) = Y(t, z)$ and $T_a(t + \Delta t, z) = T_a(t, z)$ then one recalculates X_1, X_2, X_3, X, T_g and Q with the help of equations from chapters 1 and 2.

In fact it's equivalent to dissociate the space (dz) and time (dt) integrations in the space. A step time Δt of 2 s is then admissible and the simulation of an industrial dryer on a microcomputer becomes possible.

This second method, far more rapid and simpler to apply, gives exactly the same simulated results that the precedent what confirms the validity of its supplementary hypotheses.

3.3 Simulations

The model, thus solved, allows to simulate the kinetic of drying of any deep bed taking into account the grain moisture content average on the thickness.

From the 4 adjusted coefficient K_Q, B_1, B_2 and α in the preceding chapters, only 3 keep a usefulness in deep bed. In fact one obtains as good results with $\alpha = 30 \text{ W} \cdot \text{m}^{-2} \cdot \text{K}^{-1}$.

Some experiments have been realized with deep beds of nearly twenty centimeters of thickness for a total mass of 4 to 5 kg of wet corn and according to the same methods that in chapter 2. One observes a good agreement between calculated and experimental kinetics (figure 3.2) account-held of the drying duration, experimental uncertainties and roundness errors during the simulation.

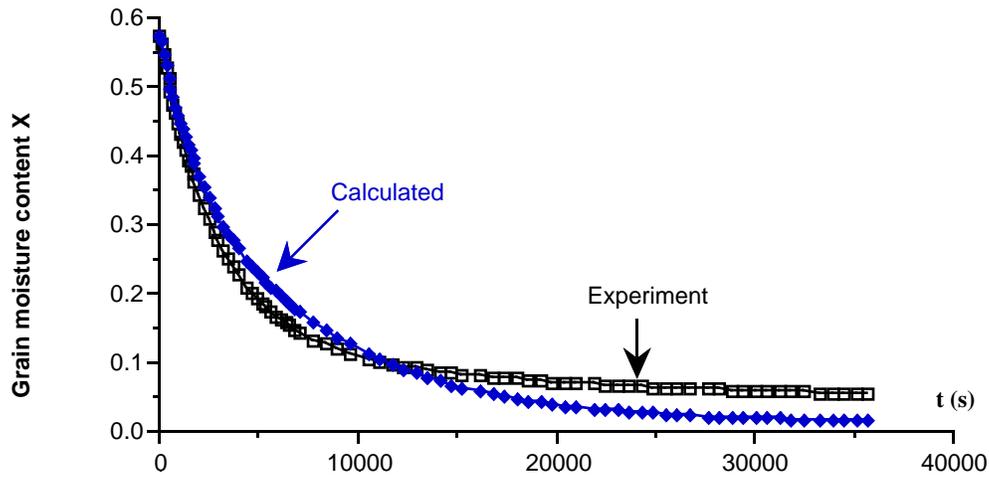


Figure 3.2: Comparison between simulated and experimental kinetics (deep bed of 0.17 m, $T_a = 100^\circ C$, $Y = 0.011$ and $V_{ahc} = 0.92 \text{ m.s}^{-1}$).

The figure 3.3 shows that the model predicts well the observed inertia in the beginning of the drying. There again, the simulation agrees quite well with the realized experiment, with the rewetted corn, in 1990 while the model coefficients have been adjusted on "thin layer" experiments of 1980 in a different air velocity domain (above 0.7 m.s^{-1}).

It should be noticed that the discontinuous weighing device of the experimental dryer (see chapter 2) provokes an artificial compression of the mass of grain, sometimes even non-uniform, during the descent of the tray supporting the product down to the weighing device.

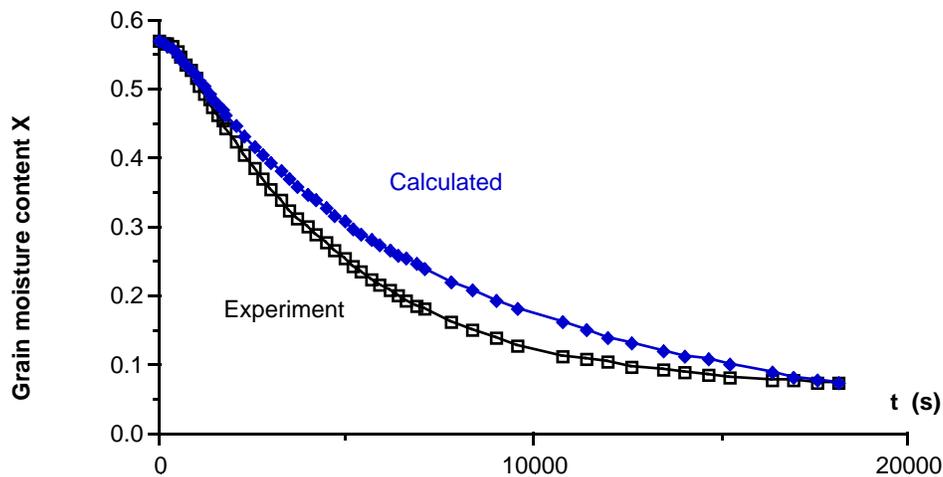


Figure 3.3: Comparison between simulated and experimental kinetics (deep bed of 0.16 m, $T_a = 100^\circ C$, $Y = 0.012$ and $V_{ahc} = 0.42 \text{ m.s}^{-1}$).

The experiment of the figure 3.3 (files FCMAIS68.CIN and FCMAIS68.FI) has been used as a basis to simulate profiles within the layer at a given instant (after 6 minutes of drying).

On the figure 3.4, after 6 minutes of drying, only the compartment 3 (surface) has truly dried. Furthermore, one observes that the drying front has progressed until approximately 8 centimeters deep; and that the evaporated water of the first layer is going to condense partly on the last layer.

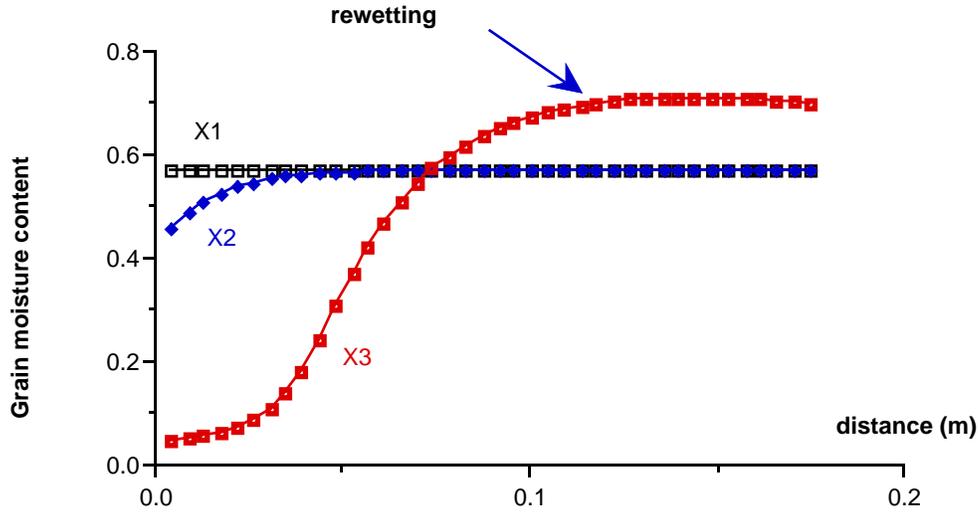


Figure 3.4: Simulated moisture content profiles of 3 compartments within the deep bed (thickness of 0.16 m, $t = 360$ s, $T_a = 100^\circ\text{C}$, $Y = 0.012$ and $V_{ahc} = 0.42$ m.s⁻¹).

In fact the condensation is, first of all, an inversion of the direction of the mass exchange : the partial pressure of vapor P_{va} in the air becomes superior than that of the grain P_{v3} . But the air arrives nevertheless to its saturation due to the fact of the heat yielded to the grain. The simulation predicts therefore the dragging of droplets to the surface of grains in the 3-4 last centimeters crossed (figure 3.5 : the air relative humidity reaches 100%).

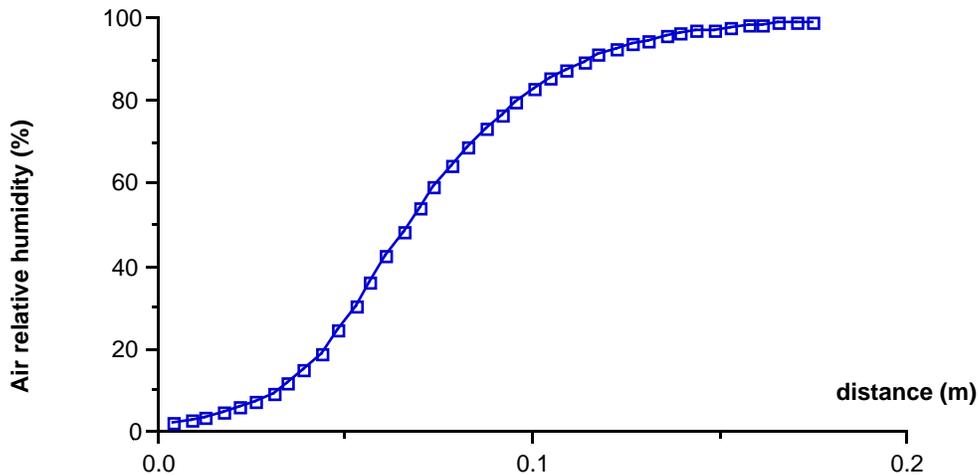


Figure 3.5: Simulated air relative humidity profiles within the deep bed (thickness of 0.16 m, $t = 360$ s, $T_a = 100^\circ\text{C}$, $Y = 0.012$ and $V_{ahc} = 0.42$ m.s⁻¹).

On the figure 3.6, one can observe the gap between grain T_g and air T_a temperatures (more the time passes more it is small) that decreases gradually within the bed to see them, both, converge to the wet

bulb temperature at the saturation of the air.

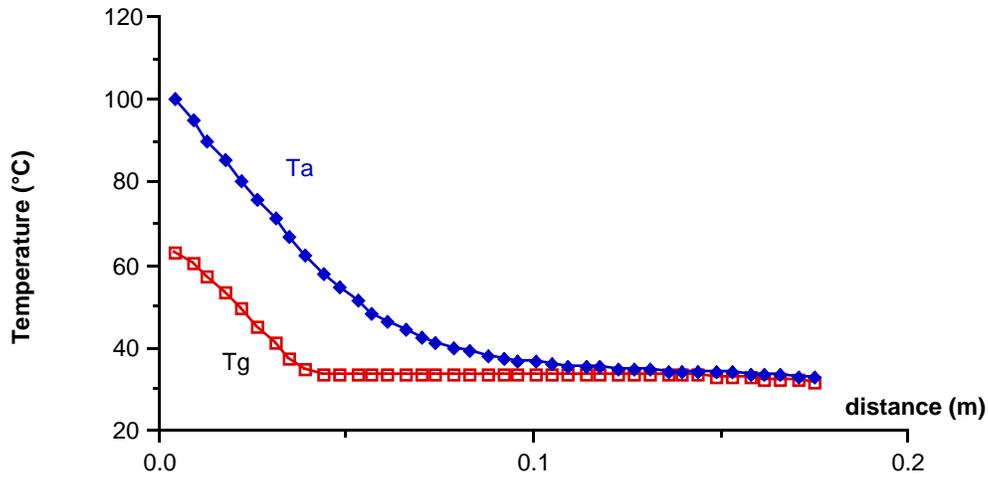


Figure 3.6: Simulated air (T_a) and grain (T_g) temperature profiles within the deep bed (thickness of 0.16 m, $t = 360$ s, $T_a = 100^\circ\text{C}$, $Y = 0.012$ and $V_{ahc} = 0.42$ m.s⁻¹).

Still simulating the same experiment, but by studying now the time axis, the figure 3.7 shows the delay between the climbing in temperature of the deep bed and the quality degradation : this degradation occurs only at temperature higher than 50°C. Initial grain temperatures are under 20°C.

All these curves issued from a same simulation are difficultly verifiable through experiment since it is impossible to instrument the inner part of the bed without modifying the air flow, the heat flows... of the system. Especially it is practically impossible to measure precisely the average wet-milling quality of the deep bed and even more its local values.

On the other hand it is possible to compare instantaneous temperature and moisture content of the used air at the exit of the deep bed at any time.

Especially on figures 3.8 and 3.9, the model predicts well the horizontal segment corresponding to the crossing of the saturation front in the deep bed, even though absolute values are offsetted.

And even more generally, the model, on curves of figures 3.8 and 3.9, decomposes well the 3 successive steps of the deep bed drying :

- initial overheating, progressive saturation of the air,
- migration of the drying / saturation front,
- final overheating and drying of the air.

Since the air velocity is very weak and saturation is reached, the dynamics of the sensor of air relative humidity should be taken in account to explain, partly, the differences between experiment and simulation (figure 3.9).

3.4 Conclusion

A numerical method to solve the equations in the space and time has been validated by comparison with 2 more complex (implicit and explicit) methods but that necessitate less hypotheses. It presents the double interest to be simple and rapid.

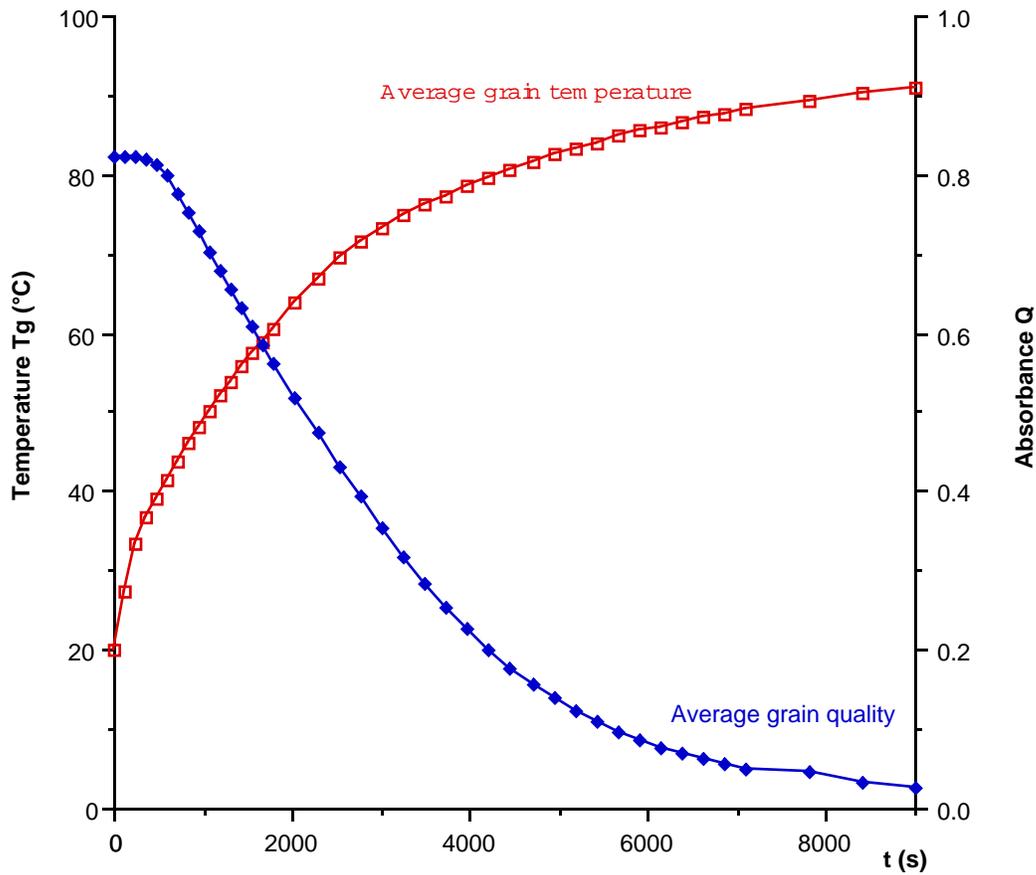


Figure 3.7: Simulated grain temperature (T_g) and quality (Q) profiles within the deep bed (thickness of 0.16 m, $t = 360$ s, $T_a = 100^\circ\text{C}$, $Y = 0.012$ and $V_{ahc} = 0.42 \text{ m}\cdot\text{s}^{-1}$).

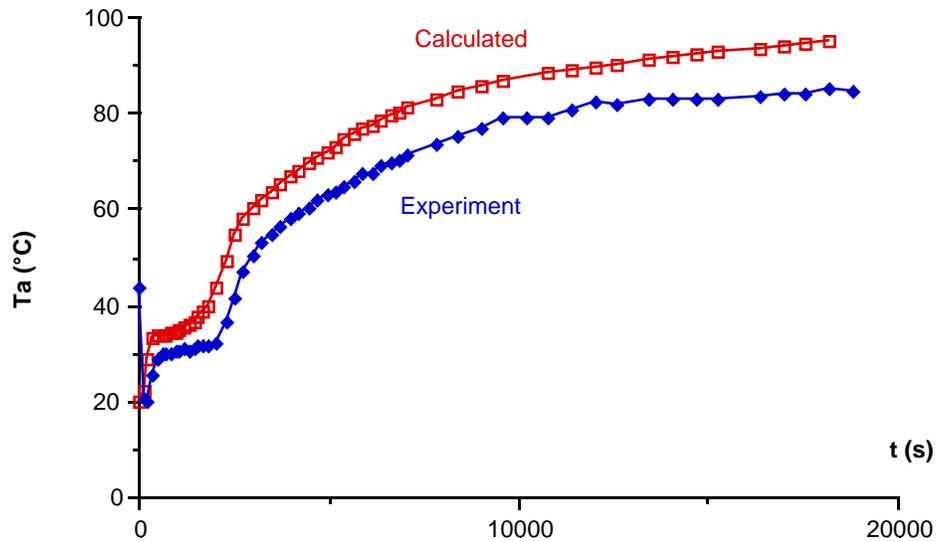


Figure 3.8: Comparison between simulated and experimental curves for the evolution of the output air temperature (thickness of 0.16 m, $t = 360$ s, $T_a = 100^\circ\text{C}$, $Y = 0.012$ and $V_{ahc} = 0.42 \text{ m}\cdot\text{s}^{-1}$).

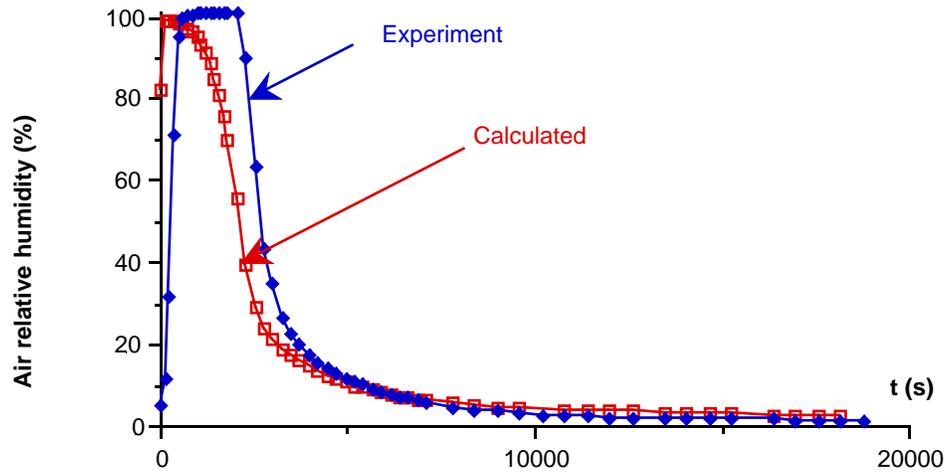


Figure 3.9: Comparison between simulated and experimental curves for the evolution of the output air relative humidity (thickness of 0.16 m , $t = 360\text{ s}$, $T_a = 100^\circ\text{C}$, $Y = 0.012$ and $V_{ahc} = 0.42\text{ m}\cdot\text{s}^{-1}$).

If one takes account of experimental uncertainties and numerical approximations, simulations agree well with experimental results without any supplementary adjustment coefficient (even one adjustment less). Especially, the model predicts well enough the air characteristics in the course of its going through the deep bed and that at any time.

The prediction of the quality has not been able to be verified experimentally but one should expect a precision loss due to the strong dependence of the coefficient of the quality degradation K_Q to the acuteness of the air temperature prediction. This prediction, from the numerical method we employed, sums all the calculation errors on the other variables.

To improve the precision, it would be interesting to redo the adjustment of coefficients B_1 , B_2 and α to integrate phenomena non taken in account such as the exchange surface decrease or the bed compression.

Chapter 4

Simulations of an industrial dryer

4.1 Steady-state

4.1.1 Bibliography

Why to simulate the steady-state of industrial dryers ? The interest is to predict, in a very short time and for a minimal cost, performances concerning wet-milling quality, moisture content, water removal flow rate and energy output of an existing dryer or design. Indeed, for this purpose, only the steady state is important.

A single simulation allows the setting of an existing dryer as a function of wet corn characteristics in entry and moisture content and quality objectives for the dried corn.

Multiplying simulations allows the development, rapid and cheap, of a new dryer more performing. It allows also to classify the different designs of existing dryers on the market.

The advantage of our model, on this subject, is important since, even if the dryer is globally in steady state, locally it is in unsteady state so that only a dynamic model can simulate.

We have been interested, for this purpose, by mixed-flow dryers, the most widespread in French corn drying manufacturers. Classically they are composed of (LASSERAN, 1977):

- one or several compartments or stages characterized by a temperature, a moisture content and an air velocity,
- one or several fans with air filters,
- an air heating device like burners with direct flame contact,
- a steam extraction device,
- a humid grain feeding device with height sensors,
- a dry grain discharge device whose functioning rate is insured by a manually adjustable timer,

Each stage has a precise function: pre-heating, drying, tempering, cooling (BRUCE, 1983).

The heated air comes from either the atmosphere or the inferior stages (recirculating of air poorly saturated).

The classical industrial dryer is generally close to twenty meters high for several meters of squared section. It results from a vertical grouping of boxes generally all identical, at least within a stage. The grain circulates there by gravity from the top to the bottom where it is extracted in a discontinuous manner so as to avoid the apparition of local stoppers and therefore fires.

In each box, one finds tidy air ducts for feeding in hot air or extraction of used air, staggered disposed. The air has therefore to cross, vertically, from a row of hot air canals to a row of used air canals, a bed (or deep bed) of grains (figures 4.1 and 4.2).

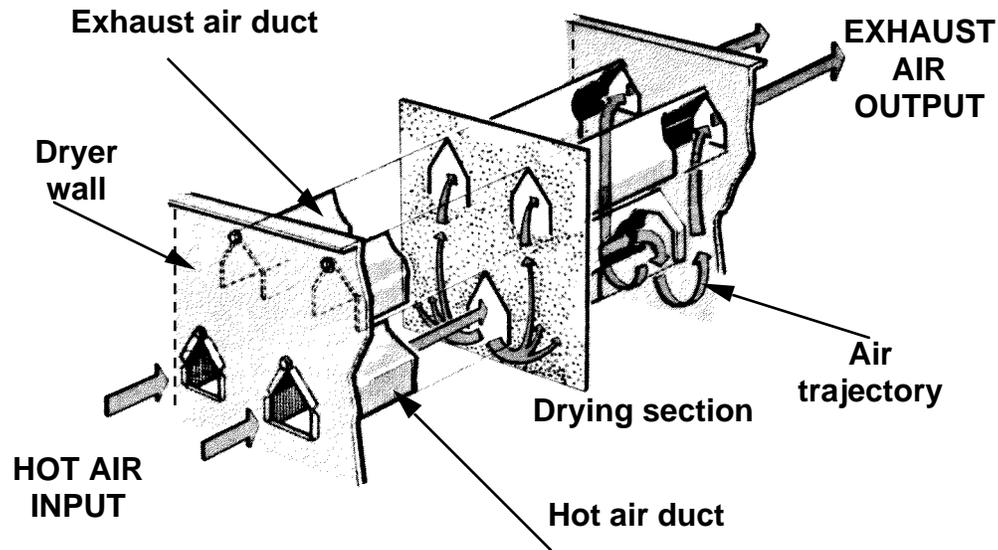


Figure 4.1: 3D View of a portion of a drying box.

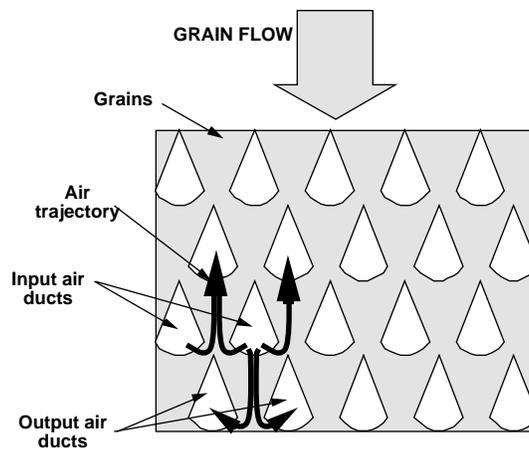


Figure 4.2: Side view of a drying box and its hot air flows.

The most often, each box of a drying stage, comprises 4 duct rows (2 of hot air, 2 of used air). And, the grain, during its descent in the dryer, encounters, in most cases, alternately these 2 types of air duct rows.

It is necessary to note that a minority of American dryers functions on this principle: the most often, the side walls of the dryer are perforated and the totality of the dryer functions in cross-flow (BAKKER ARKEMA *et al.*, 1974).

TOFTDAHL OLESEN (1987) has studied the air flow between the air ducts and evaluates air/ grains transfers to be :

- co-current flow: 32%,
- counter-current flow: 32%,
- cross flow: 36%,

in volumes of grains. But these proportions may vary according to the geometry of these air ducts and their distribution in the space.

But most of authors (BRUCE, 1983; DAUDIN, 1982) consider that to a bed corresponds a type of exchange. What is equivalent to decompose the dryer in a series of simple deep bed whose air/grain transfers are alternately co-current or counter-current flow, according to the vertical axis.

BRUCE (1989) considers that the decomposition of the dryer in deep beds whose air/grains transfers are of cross flow type, gives a better prediction of the grain temperature. Whereas it is clear that the precision of the dried product quality prediction is directly dependent on the prediction of the grain temperature.

Nevertheless, we have retained the decomposition of the dryer in deep beds alternately of co- and counter-current flow that is much more rapid to simulate and to adapt to the simulation of the dynamic regime. This implies for the model the following hypothesis: air and grain follow vertical trajectories of similar or opposite directions and then characteristics are uniform on a horizontal section. This also implies that the volume of air ducts has no "reality" (figure 4.3).

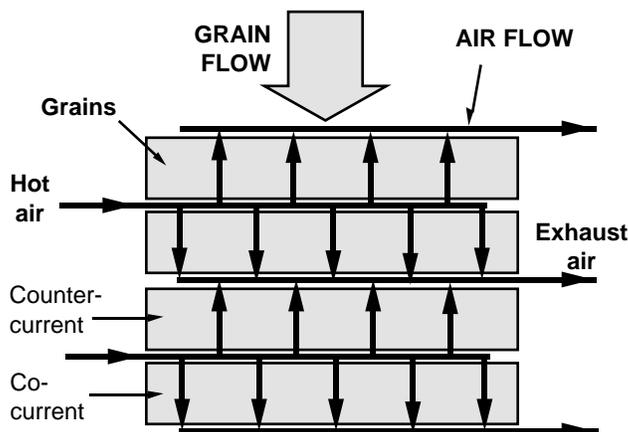


Figure 4.3: Side view of a drying box as represented in the model.

To be able to use our "deep bed" model from chapter 3, some supplementary hypotheses are therefore necessary:

- immaterial air canals: one works on an equivalent dryer volume whose air ducts volume is subtracted,
- plug-type air flow on a vertical axis,
- immobility of grain beds between 2 extractions, plug-type flow in the course of the discharge,
- negligible discharge duration (inferior to 1% of the total time),
- uniformity of the air and grains characteristics on a horizontal section,
- negligible air / grains transfers in tempering zones,

- negligible calorific losses by the walls (thermal insulation),

and, in general, hypotheses posed for the deep bed modelling are widened to the totality of the dryer.

LASSERAN (1989 b) has shown that the hypothesis of a plug-type flow was more or less verified according to dryers and that it was linked to the geometry and to the arrangement of air ducts. Results of the study of LENOIR on this flow, when they will be available, should allow to know in what cases the hypothesis is valid.

Recent works of SUN (1991) give us, now, the possibility to have a critical point of view on the hypothesis relative to the air flow.

It is necessary to insist on the fact that our model, from its construction, can not account for the specificity of the duct geometry neither even of their arrangement within a row.

4.1.2 Material, methods

Dryer pilot-plant

It is the ITCF's drying pilot-plant at Boigneville (91) that has served for experimentations.

On a height of approximately 5 meters, it is composed of boxes of dimensions 0.5 m x 0.5 m x 0.55 m whose 13.5% of the volume is occupied by 2 rows of air ducts (figure 4.4). Modular, it is generally configured in 2 drying stages, 2 tempering stages and 1 cooling stage. It can be assimilated to an industrial dryer at the scale 1/4th.

It has the following advantages, as compared to an industrial dryer:

- The air temperature and the flow rate are known and mastered for each box what is rarely the case for industrial dryers where one does not know exactly the distribution of air flows between the various boxes of a same stage.
- It is possible to function with or without air recirculating. It is also possible to choose whose boxes are used for the recirculating.
- The sensor instrumentation is important, especially air temperature and relative humidity at the input and output of each box, input air flow rate in each box.
- The screw-based discharge device allows to master precisely the grain volume extracted.

It presents also some disadvantages:

- The ducts geometry and their arrangement are fixed.
- The extraction is not instantaneous: one modifies the grain flow rate by changing the discharge duration on a one-minute cycle.
- The range of grain flow rates on the discharge timer is limited : this implies, in some cases, a manual action (on the screw motor speed reduction) unadapted for automatic piloting experiments.

Experiments of drying on this equipment have been realized by the team of the Service "Quality and Agro-Food Markets" of the ITCF under the direction of Mr. LASSERAN.

It is necessary to note that it is difficult to maintain, on a long period, the product input characteristics perfectly constant (moisture content X and wet-milling quality Q) as well as, in a lesser measure, the dryer settings (temperature T_a and air velocity V_{ahc}).

The lack of synthetic forms (or files) summarizing tests characteristics (sometimes ancient) in view of computer simulations and the necessity to operate averages on most of the variables (input grain moisture content, input air temperature. . .) increase the uncertainty on these values.

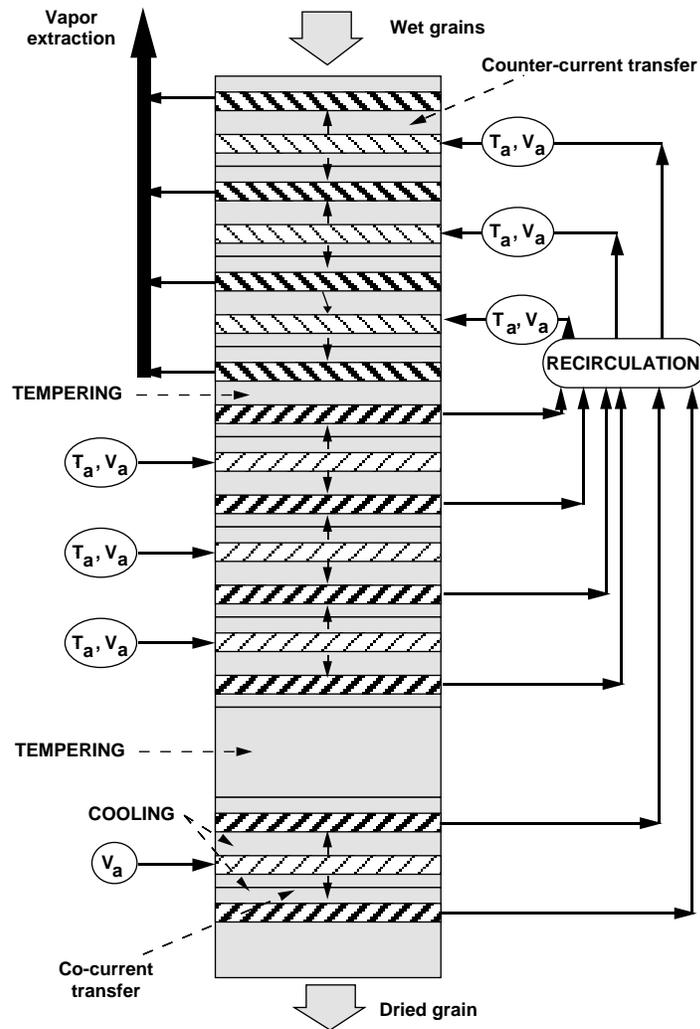


Figure 4.4: Schematic representation of the drying pilot-plant at the ITCF in the case of a configuration with air recirculating and cooling in lower part.

Numerical solution

Each deep bed height is determined by:

$$\text{Deep bed height} = \text{Box Height} / \text{Number of duct rows}$$

One works on an equal volume by subtracting the air ducts volume to the height:

$$\text{Equivalent height} = \text{Real height} \cdot \text{Filling coefficient}$$

One calculates the extraction height corresponding to the grain mass discharged at each extraction:

$$\text{Extracted mass} = \text{Grain flow rate (kg/s)} \cdot \text{Duration of an extraction cycle}$$

where the grain flow rate considered is global and includes as much extraction periods as drying periods. Furthermore, a cycle comprises an extraction phase followed by a drying phase where the grain remains immobile.

$$\text{Extraction height} = \frac{\text{Extracted Mass}}{\text{Apparent density} \cdot \text{Equivalent section area}}$$

To the extent of the discharge height is rarely a multiple of the height of a thin layer, this value is rounded and the duration of the discharge cycle is modified accordingly : the grain flow rate remains therefore identical.

The apparent density of the corn is given by MUHLBAUER (1974) for the variety INRA 258:

$$\text{Apparent density} = 853 - 252.X \text{ with } 0.1 \leq X \leq 0.6$$

It is the apparent density of the dried grain that is considered in all the dryer: by convenience, one considers that the variation of this parameter on the vertical axis influences little the result of the simulation. In fact, it does not exist any, or almost, data on the evolution of the "compacting" of the corn in the dryer (the only water loss has a weak influence on the apparent density).

One seeks for a steady state in each deep bed, one after the other, from the top to the bottom. The calculation cycle for each deep bed comprises 2 phases: drying during the interval between 2 discharges (60 s for the ITCF dryer) then offsetting corresponding to the height of extraction.

At the beginning of the calculation, the deep bed is initialized with results from the calculation of the superior deep bed.

In the case of co-current flow or tempering zones the calculation of the thin layer state, at a given instant, depends only on the state of preceding (superior) thin layer. The steady-state is therefore reached after a single renewal of the deep bed grains.

In the case of deep beds whose air/grains transfers are of counter-current flow type, more than a complete renewal is needed to observe the grain moisture content stability within the bed.

In the case of the air recirculating, one repeats the complete simulation of the dryer, integrating the used air moisture content previously calculated, until stability is reached.

Simulations are realized to obtain the desired moisture content at the bottom of the dryer: the discharge cycle duration (and therefore the grain flow rate) is optimized accordingly (iterative search).

All calculations have been realized on an APPLE MACINTOSH II SI equipped with a 68030 micro-processor at 20 MHz and a 68882 floating-point unit, bringing a power of approximately 1 Mips (million of instruction per second). The program has been realized in THINK PASCAL version 4.0.

The complete simulation of the ITCF's dryer necessitates 2 to 15 minutes of calculation (one hour in the case of the reorienting of air) according to the grain flow rate and the air temperature considered. This duration lengthens with the air recirculating and the dryer height. The time and space step sizes used are respectively 1 s and 0.005 m generally. The result of a simulation is represented by a table containing more than 7000 variables relative to the grain and to the air.

4.1.3 Results

Due to the important calculation time and the numerous data to analyze, our study has concentrated on 2 experiments realized at the ITCF in 1987 and in 1988 with very different dryer configurations and settings.

Table 4.1: Test 1 / 1988 - comparison between experiment and simulation (wet-milling quality expressed in % of transmission). Results are bold faced.

TEST 1 / 1988		Experiment	Simulation
Dry grain flow rate		$140 \pm ? \text{ kg/h}$	134 kg/h
Inputs	Moisture content X	$0.532 \pm ?$	0.532
	Temperature T_g	$34 \pm 2^\circ C$	$34^\circ C$
	Quality Q	$25 \pm ?\%T$	$15\%T$
Outputs	Moisture content X	$0.187 \pm ?$	0.187
	Temperature T_g	$16 \pm 2^\circ C$	$20^\circ C$
	Quality Q	$85 \pm ?\%T$	$83\%T$

The figure 4.5 represents schematically the physical configuration of the dryer, its settings and the result of the test 1 / 1988. The wet-milling quality is here expressed in percentage of the transmitted light (%T) since it is the unit commonly used in the corn industry to express the result of the test of turbidity (see chapter 1).

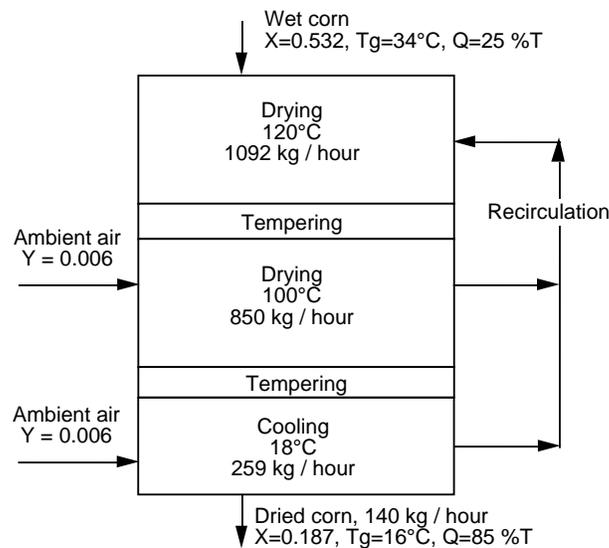


Figure 4.5: Test 1 / 1988 - configuration and settings of the drying pilot-plant at the ITCF (wet-milling quality expressed in % of transmission).

The simulation of this test necessitates in fact several simulations repeated until the stabilizing of the moisture content of the recycled air and the obtaining of the grain moisture content observed experimentally. It is elsewhere important to note that, on this test, the air recirculating influences very little the dried grain characteristics. This confirms the economic interest of the recirculating.

By comparing the simulation to experimental results (table 4.1), one observes:

- moisture content X of the simulated and experimental dried product are, by construction, identical,
- the measured temperature T_g of the dried product is predicted with an error inferior to $4^\circ C$,
- the experimental wet-milling quality Q of the dried product is predicted with an error close to $2\%T$,
- the essential of the distance between simulation and reality is "concentrated" on the dry grain flow rate (4% of gap).

Table 4.2: Test 2 / 1987 - comparison between experiment and simulation (wet-milling quality expressed in % of transmission). Results are in fat.

TEST 2 / 1987		Experiment	Simulation
Dry grain flow rate		97±? kg/h	87 kg/h
Inputs	Moisture content X	0.546±?	0.546
	Temperature T_g	30 ± 4°C	30°C
	Quality Q	27±?%T	27%T
Outputs	Moisture content X	0.189±?	0.189
	Temperature T_g	16 ± 2°C	19.8°C
	Quality Q	79±?%T	78.1%T

The test 2 / 1987 is very different from the precedent (figure 4.6): lower drying temperature and no air recirculating.

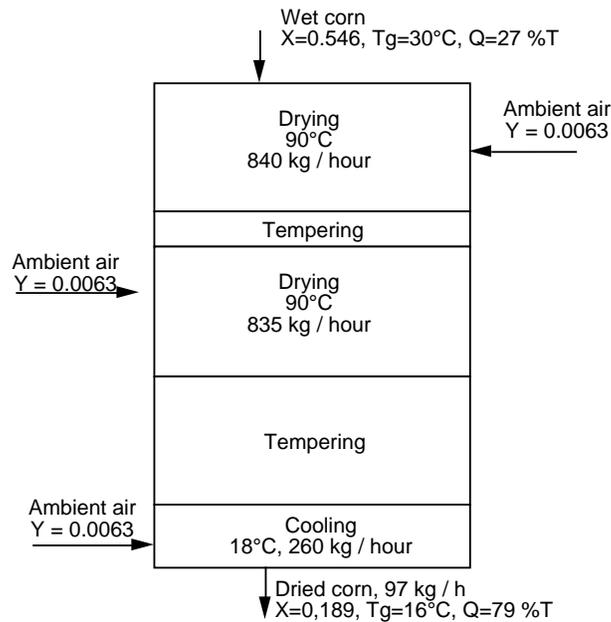


Figure 4.6: Test 2/ 1987 - configuration and settings of the drying pilot-plant at the ITCF (wet-milling quality expressed in % of transmission).

There again, the model predicts moisture content X , temperature T_g and wet-milling quality Q of the dried corn with a very good precision (table 4.2). Observed error between simulated and real dry grain flow rates is close to 10%.

The results of this last simulation will be discussed in detail now. The abscissa axis of the next curves represents the distance covered by the grain since the top of the dryer: it represents also the time axis (if divided by the grain velocity). Vertical gray lines indicate the location of the input and output air ducts.

When studying the evolution of the output air relative humidity along the grain trajectory (figure 4.7), several remarks arise:

- The relative humidity of the used air reaches 100% at the top of the dryer what confirms the experiment.
- The relative humidity of the used air increases after the first zone of tempering : this confirms a improved drying rate at the resumption.

- The relative humidity of the used air decreases after the second zone of tempering: its role is therefore rather negative since it does not improve the drying at the resumption while the grain degrades nevertheless under the effect of its own temperature.
- The relative humidity of the used air in 60% of the dryer is inferior to 30%: it would be better to decrease the air flow rate in these boxes or to recycle it to superior boxes to increase the energy output.

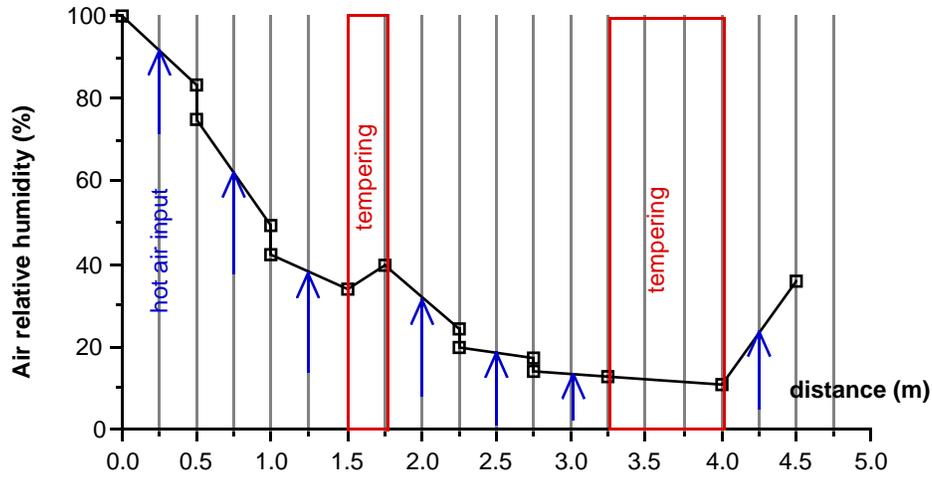


Figure 4.7: Test 2 / 1987 - simulated evolution of the relative humidity of the used air in output air ducts (abscissa oriented from the top to the bottom of the dryer).

The figure 4.8 confirms the economic interest of a recirculating of the used air from the lower part of the dryer: the temperature exceeds 50°C on this zone (excluding cooling).

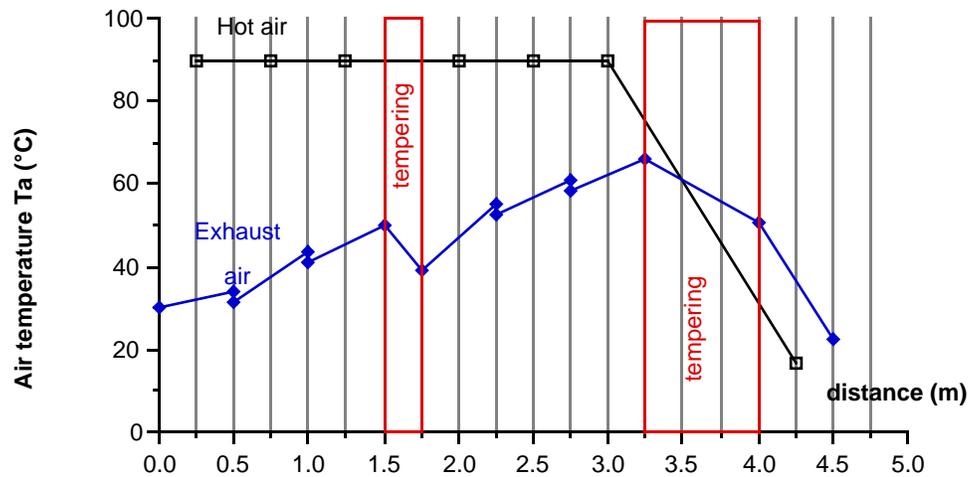


Figure 4.8: Test 2 / 1987 - simulated temperature evolution of the input and output air in input and output air ducts (abscissa oriented from the top to the bottom of the dryer).

The study of the curve on the figure 4.9 indicates that, on approximately 1 m height in debut of drying, the moisture content of the grain really decreases only at immediate proximity of hot air ducts. A higher air flow rate would avoid these dead zones within the first deep beds.

The curve of the figure 4.10 is of a far more complex interpretation:

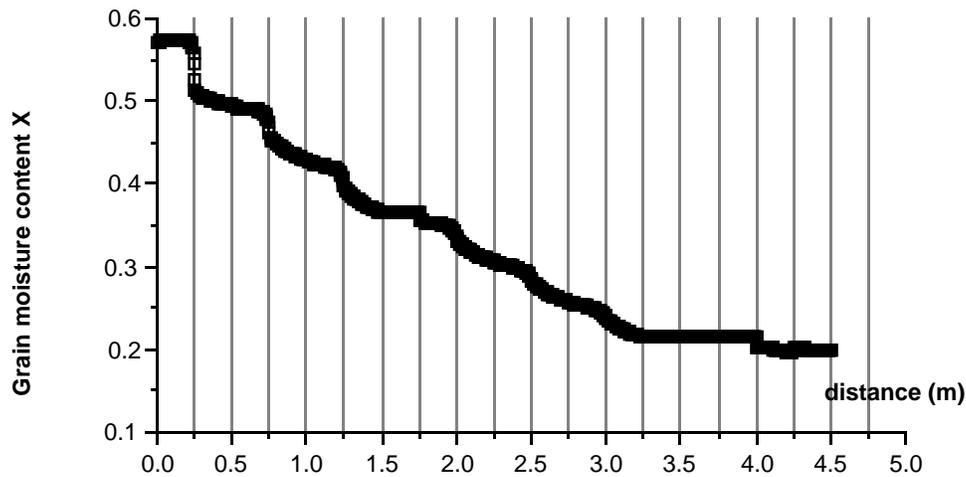


Figure 4.9: Test 2 / 1987 - simulated evolution of the grain moisture content X in the course of its descent (abscissa oriented from the top to the bottom of the dryer).

- The temperature of the grain varies continuously in the course of its trajectory, even then in a sharp manner at the proximity of hot air ducts.
- Only the first deep bed presents an isenthalpic drying : energy brought by the air serves entirely to vaporize the water (output air at 100% of relative humidity on the figure 4.7).
- For all the other deep beds, the grain temperature presents an extremum close to the arrival of the hot air.
- One notes the presence of 2 singular points (at 1.75 m and 4 m) corresponding to a numerical discontinuity between the bottom of a tempering zone and the top of the next deep bed (counter-current).

This discontinuity is related to the method employed, de-materializing of the air ducts especially, and is close to the problems met by SUN (1991) and ARNAUD and FOHR (1991) during the calculation of the maximal air velocity observed between 2 air ducts.

Its influence on results is very weak because localized on few centimeters of grain thickness. The dynamic method employed in the second part of this chapter allows to avoid this light gap.

The figure 4.11 confirms the under-drying observed until 1 m approximately since the wet-milling quality is only slightly degraded.

More, from a distance of 1.25 m, it is clear that "co-current" beds are the place of an accelerated degradation of the wet-milling quality.

Obviously, the analysis of the simulation results is particularly complex since interactions between the various variables are numerous.

This, added to the quite long computations required, has limited the number of experiments tested by the model.

4.1.4 Conclusion

The dynamic model developed in preceding chapters, adjusted on thin layer experiments in constant conditions dating 1980, allows, in 1991, to simulate completely the stationary regime of a small-scale

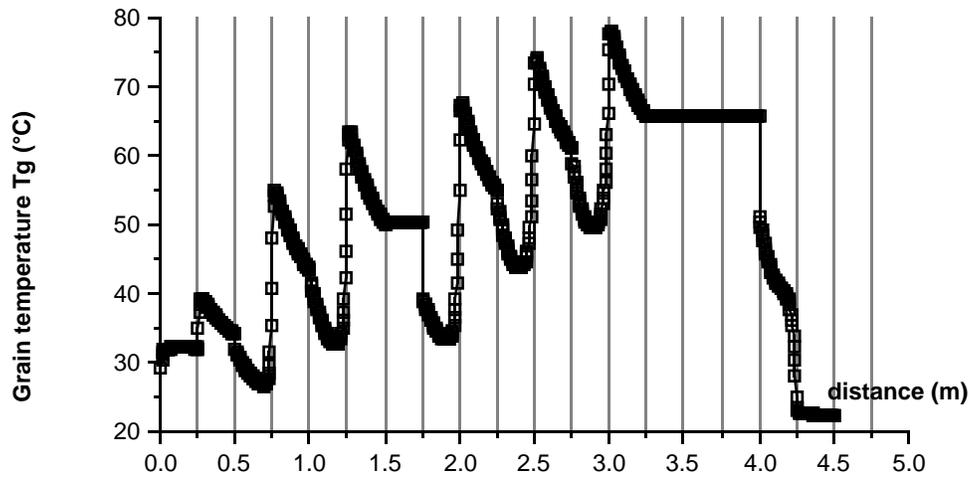


Figure 4.10: Test 2 / 1987 - simulated evolution of the grain temperature T_g in the course of its descent (abscissa oriented from the top to the bottom of the dryer).



Figure 4.11: Test 2 / 1987 - simulated evolution of the grain wet-milling quality Q in the course of its descent (abscissa oriented from the top to the bottom of the dryer).

dryer 5 m high. Locally, the numerous transitory phenomena met by the grain fully justify the preference for a dynamic model.

The program allows the prediction, in less than one hour on a microcomputer, of the steady state of any kind of corn mixed-flow dryer, existing or not. The error on the wet-milling quality prediction is very weak. The gap between simulated and experimental dry grain flow rates varies between 2% and 15%.

The adaptation of this program on a workstation 20 times faster should allow to test the model on more types of dryers and settings.

It should be thus possible to find an adjustable parameter allowing to account for the influence of the geometry and configuration of the air ducts.

From this point of view, there is an obvious complementarity between our works and those from teams of ARNAUD and FOHR at Poitiers and FLICK and CHAABOUNI at Antony.

4.2 Unsteady-state

4.2.1 Bibliography

Why to simulate the functioning of an industrial dryer in unsteady state?

After having been interested in the optimization of the design and the adjustment of dryers, it was necessary to study the optimization of their control (COURTOIS, 1990).

Our dynamic model, built to represent the dynamic behavior of a dryer, has appeared as a preferential development tool of an automatic control algorithm.

A purely experimental approach is, for several reasons, very expensive :

- It can be made only during 4 to 6 weeks in the year because, out of this period, it is not possible to rewet enough corn.
- It requires a huge grain volume, whose cost is not negligible.
- It necessitates at least 2 persons 24 h a day during several days.
- The energy cost is very expensive.
- It necessitates the immobilizing of the industrial dryer during a part of the corn campaign for this only purpose.
- Experiments are limited by the harvested corn characteristics.
- The test of several control strategies is practically impossible.

Our approach has therefore aimed to develop a computer tool allowing to reduce the experimental phase practically to the only validation of the automatic control algorithm.

To realize the simulation program, the same hypotheses that for the prediction of the steady state have been used, with an exception: the steady-state is no longer assumed.

Before to study the dynamic behavior of the dryer, it is necessary to delimit the system frontiers (figure 4.12):

- The "corn dryer" system is delimited physically by the dryer walls.
- The system is composed of dryer, contained corn and air.

- All variables relative to the corn and to the air, at input or output, of the dryer are external to the system.

The dynamic model describes dynamic relationships that exist between external and internal variables.

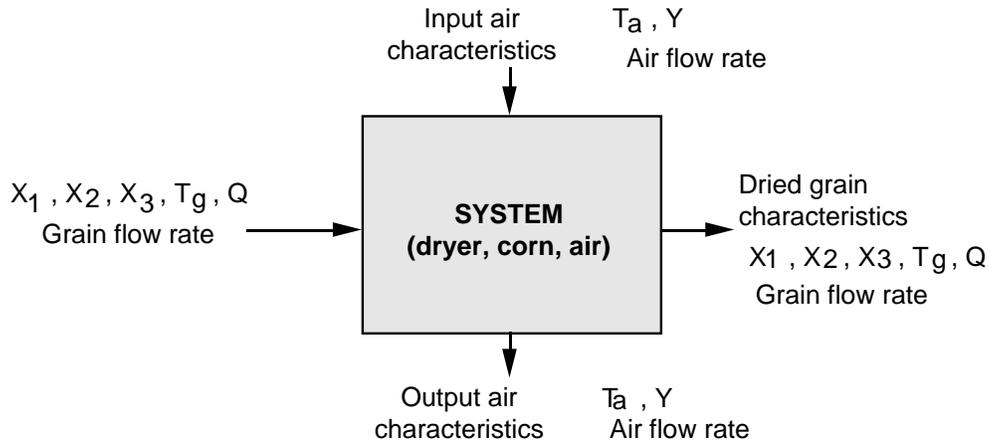


Figure 4.12: Functional representation of the dynamic system studied.

In a second time, we have simplified the study of this multi-variables system taking into account (figure 4.13) that the controlled variable is the output grain moisture content and the manipulated variable is the grain flow rate.

It is the general case for corn industrial dryers, where one modulates manually the grain flow rate to stabilize the dried grain moisture content of the grain at the setpoint value (open-loop).

The influence of all other variable is considered as a disturbance.

In fact, we have widened the system by attaching its controller to it. Our model is entirely capable to simulate the functioning of the dryer, corn, air and controller system (close-loop control).

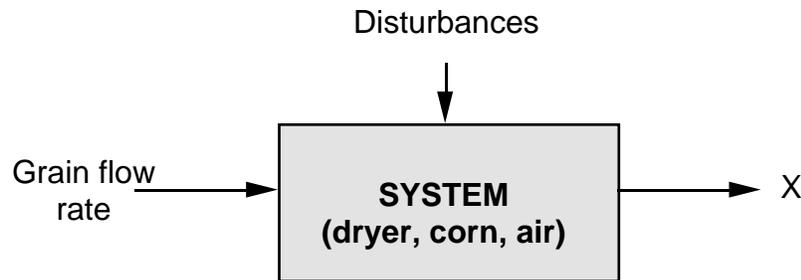


Figure 4.13: Simplified representation of the dynamic system studied.

In practice, an operator control its dryer at 3 levels:

- He chooses the drying temperature setpoint as a function of the compromises between desired wet-milling quality and dry grain flow rate,
- He modifies the discharge rate (and therefore the grain flow rate) to obtain the desired moisture content in exit,
- He changes his preceding strategy to avoid over-drying phases degrading considerably the wet-milling quality, or even the commercial quality (presence of dark grains).

It is evident that this manual method requires a strong experience and a continuous attention 24 h a day.

MARCHANT (1985) has summarized criteria that has to verify any control system, automatic or non:

- Precision: the average value of the dried grain moisture content has to be close to the objective fixed by the operator.
- Rapidity: any disturbance and especially any change of grain moisture content in entry has to be compensated rapidly in exit.
- Stability: the system mustn't present too large oscillations (it shouldn't diverge).
- Robustness: the system has to remain performing on a large drying domain.

To which it is necessary to add:

- Fidelity: the dispersion of the moisture content of the dried grain has to be weak.
- Preservation of the quality: the system has to avoid over-drying phases that damage the corn wet-milling quality.

Classically, one can use a PID controller (proportional, integral, derivative) to stabilize the output product moisture content directly or indirectly through the used air temperature quite well correlated depending on the sensor location (bottom of the dryer).

It makes an inexpensive and simple solution, well known, but that satisfies only to the first 2 conditions. Experimented at the ITCF nearly 15 years ago, it is generally used for the control, close to a stabilized functioning setpoint, the used air temperature at the dryer bottom, through the command of the discharge rate.

But it is more interesting to use the available knowledge on the process (the model) to automate it. This is why we have followed this approach.

Among the numerous drying model, most make the steady-state hypothesis. In fact, they are not well suited to describe the unsteady state observed on a dryer during a disturbance for example. They can normally predict only the new steady state that appears after this transition.

Even dynamic models of PLATT *et al.* (1991) or MOREIRA and BAKKER ARKEMA (1990) make, indirectly, this hypothesis since they use an empirical drying equation adjusted on thin layer kinetics in constant conditions.

But, it is necessary to notice that American dryers are of simpler design (no air ducts in the grain mass) and the American corn, less humid, necessitates a drying amplitude far more limited than in France, or at least in the north part of our country. In these conditions, it is understandable that their models render correctly the dynamic behavior of the dryer.

As far as we know, in the domain of cereal drying, only our model is truly dynamic from the thin layer to the industrial dryer levels.

Generally the model is linearized around a setpoint and, by a technique of pole-placement, a linear controller is defined.

This way, ELTIGANI and BAKKER ARKEMA (1987) study a linear controller with feedforward effect (anticipation by the moisture content of the grain in entry) and feedback effect (correction by the moisture content of the grain at the exit) to stabilize the output grain moisture content.

NYBRANT (1988) brings an improved robustness to the system : its controller is an adaptive one. It recalculate its parameters in real time. But it controls the used air temperature and not the dried grain moisture content.

MOREIRA and BAKKER ARKEMA (1989) use an adaptive feedforward + feedback controller on the grain moisture content. Their results, on an American cross-flow dryer, seem interesting but hardly adaptable to mixed-flow dryers.

But, to all these works, one can oppose following remarks:

- They are conceived for dryers of quite a different technology, often simpler.
- They are tested generally on pilot-plants of very limited sizes, with much lower drying amplitude than those met in France.
- Authors give generally only the general lines of their works and remain unprecise on the "material and methods" chapter.

The AFRC (Silsoe, England) institute has well enough described its approach in many reports (WHITFIELD, 1987a and b). And, although it has worked on the wheat and with very limited drying amplitude, the method employed, simple and shrewd, seemed interesting to us for our corn dryers.

The AFRC controller is a typical PI (proportional, Integral). But from theoretical knowledge on the drying, the robustness is increased by a pseudo-linearizing of the system.

The starting point is that the open-loop system is non linear and therefore that a classical controller does not suffice. For the linearizing, one starts from the idea that any drying kinetic can be approximated by an exponential. What one can translate into:

$$X = k1. \exp(k2.t) \quad (4.1)$$

where X is the dried grain moisture content, t is the residence time of the grain in the dryer and $k1$, $k2$ are 2 parameters to optimize.

or

$$X = k1. \exp\left(\frac{k2'}{\text{grain flow rate}}\right) \quad (4.2)$$

that one can linearize as :

$$\log(X) = k1' + \frac{k2'}{\text{grain flow rate}} \quad (4.3)$$

Finally, with a technique of pole-placement, the controller can be written as,

$$\frac{1}{\text{Grain Flow Density}} = K_R. \frac{z - a_R}{z - 1}. [\log(X_t) - \log(X_{\text{setpoint}})] \quad (4.4)$$

where K_R is the proportional parameter, a_R is the integral parameter and z is the Z-transform variable.

The use of the flux density instead of the grain flow rate allows, at least partly, to get rid of the specific characteristics of the dryer studied.

Using our dynamic model to control, in real time, the dryer requires expensive computations. This is why we have retained this algorithm initially conceived for wheat mixed-flow dryers.

The dynamic model no longer serves to pilot directly the dryer but to conceive and test the best control algorithm.

In our study, the objective for the controller development has been to seek for a critical damping (without over-drying) in less of twice a residence time, with a dried corn moisture content (wet basis) controlled within 0.5 point.

4.2.2 Material, methods

Instrumentation of the ITCF dryer

The handling devices of the ITCF's dryer pilot-plant at Boigneville has been modified to allow the installation of two on-line grain moisture sensors.

These devices, from SERDIA, function on the principle of dielectric constant measure of the grain + air situated between 2 half-cylinders of vertical axes. This measure, for many products, is well related with their moisture content.

Their size, necessitating nearly ten kilograms of corn to give a reliable measure, is not well suited for dryer pilot-plants : several extractions are necessary to fulfill the sensor at the dryer output.

This problem has been partly solved with the help of a small electrical automata controlling, in real-time, the filling and the draining of the sensor at the dryer output.

The figure 4.14 shows the information trajectory. The indirect measure from sensors is transmitted to the SERDIA computer where it is converted, according to the calibration curve in moisture content (% wet basis). This value is transmitted to the main computer, dryer controller, that computes a new command of grain flow rate translated as a discharge rate to the extracting device, through a Numeric / Analog Converter (HP).

It is necessary to specify that these sensors are the only one available on the french market, at least at an accessible price and that the constructor has adapted its software to fit our needs.

Numerical methods

The only difference, as compared to the method used to describe the steady state, resides in the fact that it is here necessary to recalculate the totality of the dryer at each time.

This leads to large calculation times: up to 1 s of calculation to simulate 1 s functioning of the dryer.

Equation 4.4 translates numerically into the relationship :

$$\frac{\text{Dryer Section Area}}{\text{Grain flow rate at } t + \Delta t} = K_R \cdot \left[\log \left(\frac{X_{t+\Delta t}}{X_{setpoint}} \right) - a_R \cdot \log \left(\frac{X_t}{X_{setpoint}} \right) \right] + \frac{\text{Dryer Section Area}}{\text{Grain flow rate at } t} \quad (4.5)$$

where, here, Δt represents the sampling period (different from the calculation step size of the simulation).

4.2.3 Results

Study of the open-loop system

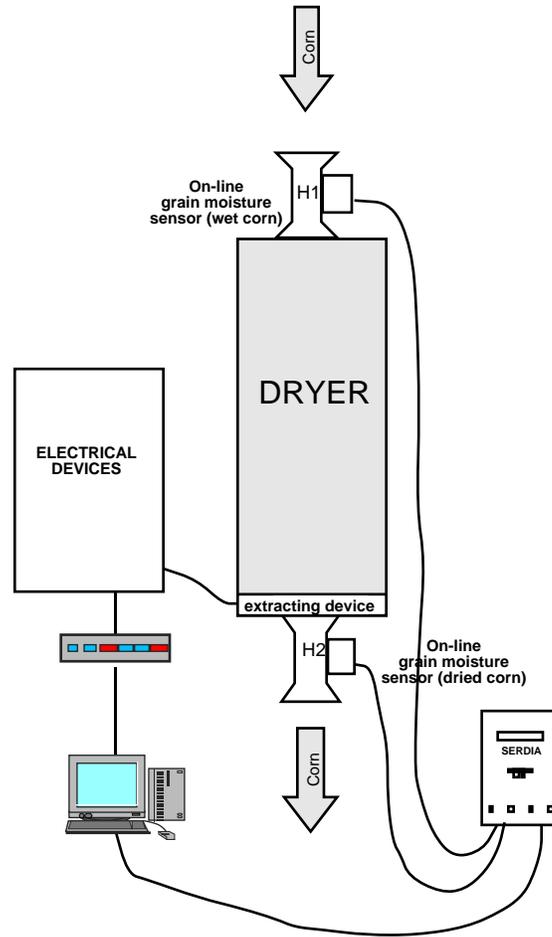


Figure 4.14: Close-loop of the ITCF's pilot-plant.

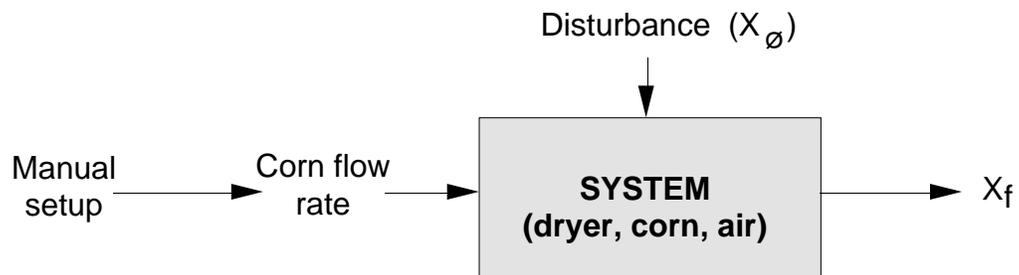


Figure 4.15: Functioning of the open-loop system.

The simulation of the behavior of the dryer, not controlled (open-loop system : figure 4.15) and in unsteady state, allows to characterize it. It is a first necessary approach before obtaining a control algorithm.

A first test consists in predicting the evolution of the dried grain moisture content during a step change of grain flow rate (sharp increase of 15%).

The obtained response curve (figure 4.16) is of chaotic type. This comes from the discharge mode retained for the dryer : each variation of the grain flow rate is translated into a modification of the height of grain extracted with a fixed frequency. Since air ducts are regularly spaced, when the dryer reaches its steady state, the grain is in phase with them. The change of extraction height provokes then a phase shifting responsible for this chaotic curve.

Discontinuities observed on the response curve (figure 4.16) justify the need for a non-linear controller.

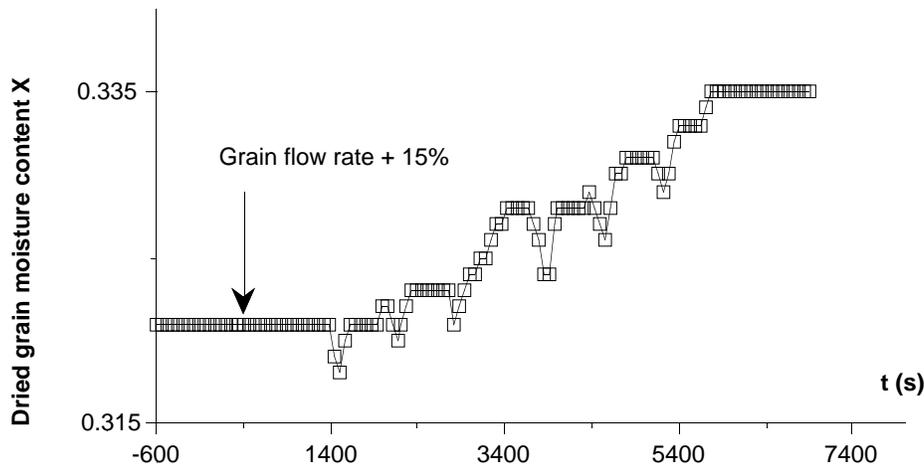


Figure 4.16: Response curve simulated in the case of a step change of grain flow rate (simulation based on the test 7 / 1988).

The study of the experimental response curve of the dryer in the case of a step change of grain flow rate of 16% (in different conditions from the preceding simulation) is also characterized by a chaotic shape (figure 4.17).

Nevertheless, it is difficult to conclude to the equivalence of these 2 curves since, in the case of the experimental curve, many parasitic phenomena influence the final measure (variation of characteristics of the wet corn, residence time distribution...).

The study of simulated response curves resulting from different step changes of grain flow rate (figure 4.18), has allowed to characterize the system:

- non-linear: both on the static gain and by the presence of a hysteresis phenomenon between negative and positive steps,
- high pure delay (several hours),
- order higher than 2.

The dynamic model allows, moreover, to test the sensibility of the dryer to the various disturbances especially the variations of the wet corn moisture content (figure 4.19). Thus, the curve corresponding to the step change $X + 50\%$ presents a sharp climbing justifying again the need for a non-linear controller.

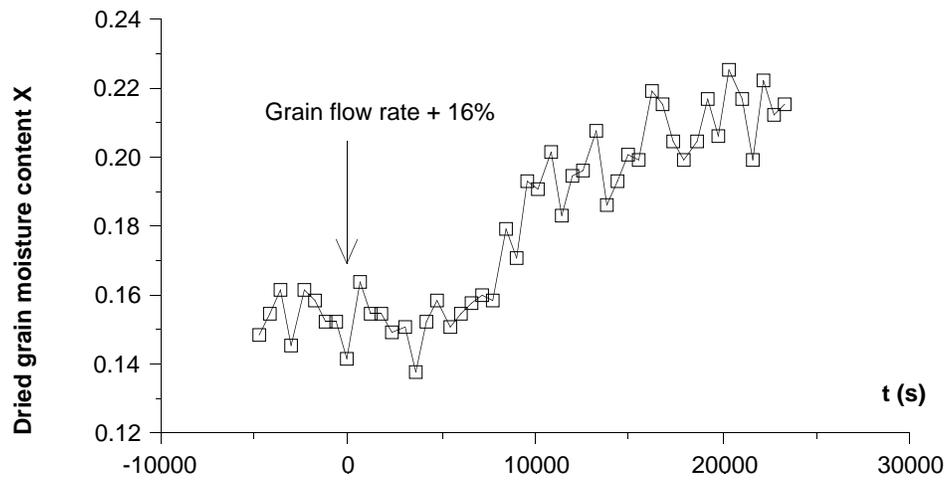


Figure 4.17: Experimental response curve in the case of a step change of grain flow rate (Test 3 / 1986).

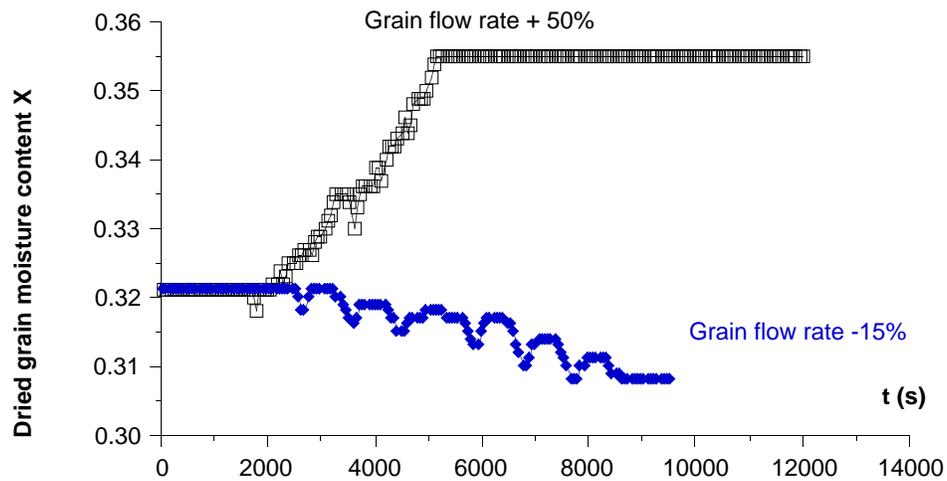


Figure 4.18: Simulated response curves in the case of step changes (at $t = 600$ s) of grain flow rate (simulations based on the test 7 / 1988).

It is necessary to note that obtained curves reflect well the assumptions used to simulate them: the grain descends according to a plug-type flow. In the reality, in addition to to be noisy, curves would be more dispersed on the time axis.

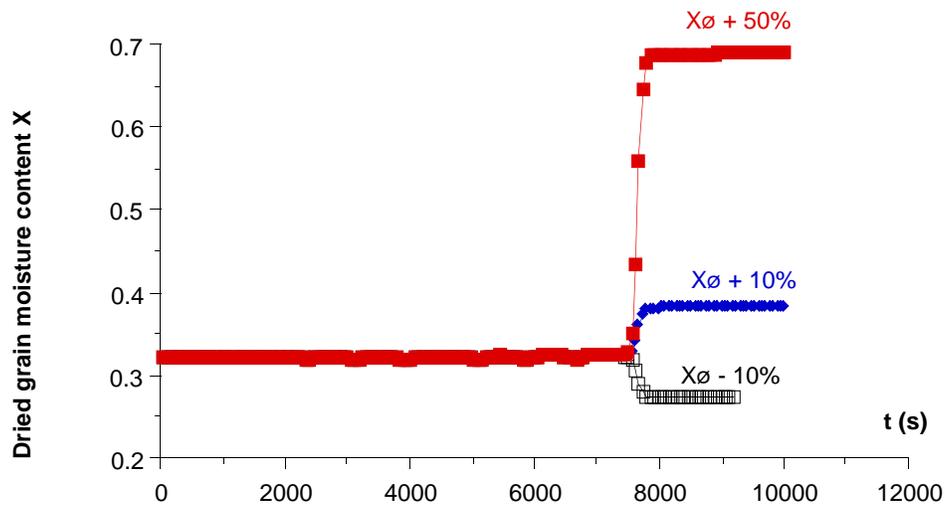


Figure 4.19: Simulated response curves in the case of step changes (at $t = 600$ s) of wet grain moisture content (simulations based on the test 7 / 1988).

In fact, the program allows to simulate the response of the dryer to any disturbance. Each variable evolution is calculated and thus can be studied.

Study of the close-loop system

The model can also be used to study the controlled system (close-loop).

The figure 4.20 schematizes the functioning of the controlled system by the AFRC's algorithm.

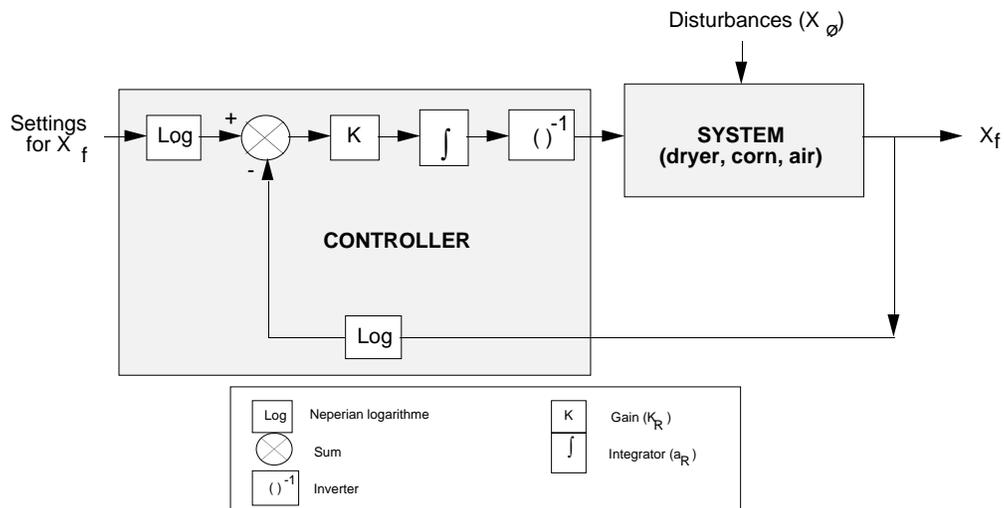


Figure 4.20: Functioning of the close-loop system.

If it is not aberrant to preserve the same sampling period (300 s), before to experiment the controller on the pilot-plant, it has been necessary, jointly, to test the algorithm and to identify parameters K_R and a_R .

Simulations of the figure 4.21 are obtained by imposing a change of setpoint on the final grain moisture content for the controller at the time $t = 600$ s. The dryer is beforehand stabilized on data coming from the test 7 / 1988.

The influence of the controller parameters appears clearly on this figure where one observes a better damping for the couple ($K_R = 0.01$, $a_R = 0.7$).

Due to the simulation slowness, the research of the optimal parameters has been made by successive tests.

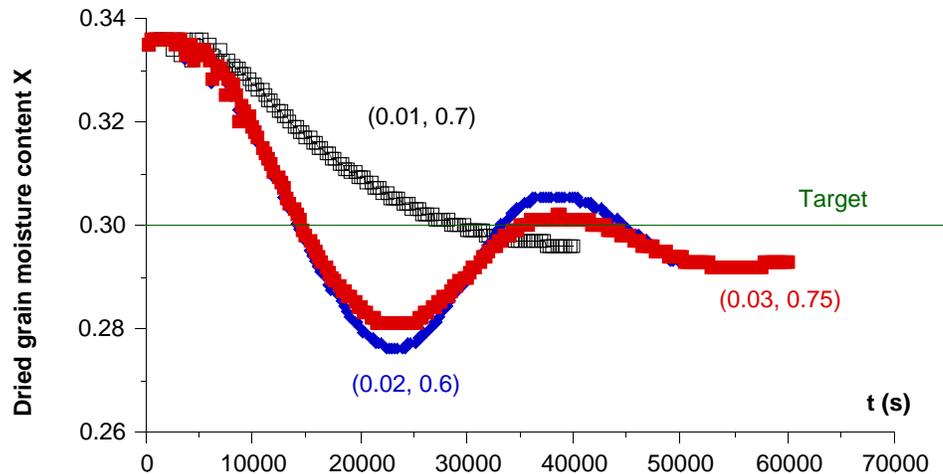


Figure 4.21: Influence of the controller parameters (K_R , a_R) on its performance (simulations based on the test 7 / 1988).

Using these parameters, *a priori* adequate, the controller has been truly tested, on the dryer pilot-plant.

The experimental evolution curve of the dried grain moisture content on the figure 4.22 indicates that the controller does correctly the setpoint change in a suitable time (the residence time of the grain increases approximately from 15 000 s to approximately 50 000 s).

The experimental evolution curve of the dried grain flow on the figure 4.22 illustrates how the controller makes the dryer slip from a steady state to another.

Simulations has appeared in good agreement, qualitatively, with experimental results. But a more powerful computer would have allowed to compare precisely each experiment with its associated simulation.

After a series of short experiments on the pilot-plant, the parameters have been slightly modified: the couple of values (0.01, 0.7) has been replaced by (0.012, 0.75) appreciably better suited to the studied domain of grain moisture content.

A 5-days experiment has then been realized with the participation of the whole Service "Quality and Agro-Industrial Market" at the ITCF. In function of the available corn characteristics, a rough "experimental design" has been developed, then modified during the experiment depending on the numerous practical constraints met.

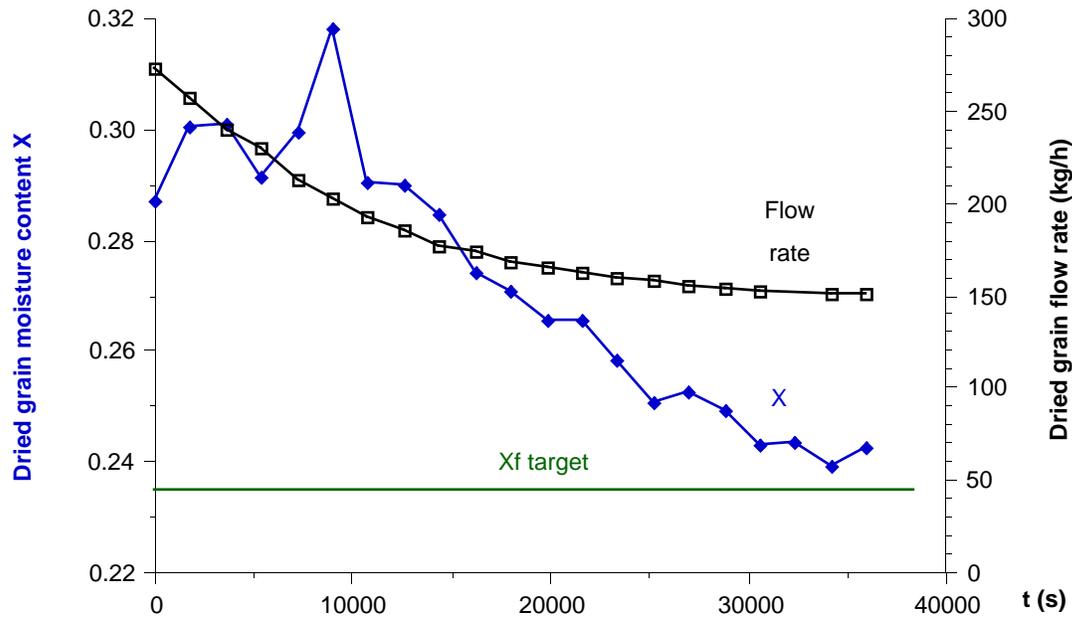


Figure 4.22: Evolution of the flow rate and the moisture content of the dried grain in the course of an experimentation (test 5 / 1990).

The test 7 / 1990 (figure 4.23) comprises several phases:

- search for a stationary regime in manual mode, production of a half-dried corn,
- start of the controller with for objective: to make the dried grain moisture content decrease from $X_f = 0.300$ to 0.282 , what has been perfectly realized,
- new radically different objective for the controller : $X_f = 0.176$ what provokes oscillations damped quite rapidly,
- step change of the wet grain moisture content from $X_i = 0.450$ to 0.280 (recirculating of the half-dried grain): the controller damps well the disturbance.

A very important phenomenon has appeared during this test: the dried grain moisture content sensor had to be re-calibrated very often to avoid any drift. But each re-calibration provokes a disturbance on the controller (see on figure 4.23 : between 150 000 and 175 000 s) delaying systematically the stabilizing of the dryer.

This problem is largely responsible for the non optimal response time of the close-loop and it would be good to improve the sensors in order to facilitate this work. It would be useful, also, to combine instantaneous grain moisture content measures with alternate measures (temperatures of used air...) to strengthen the information used by the controller.

The controller speed is acceptable (1 to 3 grain residence time) and explained essentially by the lack of a feedforward (the wet grain moisture sensor is not used for the control).

The controller seems not be enough robust since it has provoked oscillations during of the second change of setpoint. But it is necessary to specify that the normal functioning of an industrial corn dryer does not present such large variations of objective. This controller, in these conditions, seems well suited.

A very important point should be incorporated in the controller : the wet-milling quality of the dried corn has to be taken in account as a supplementary constraint or directly as an objective.

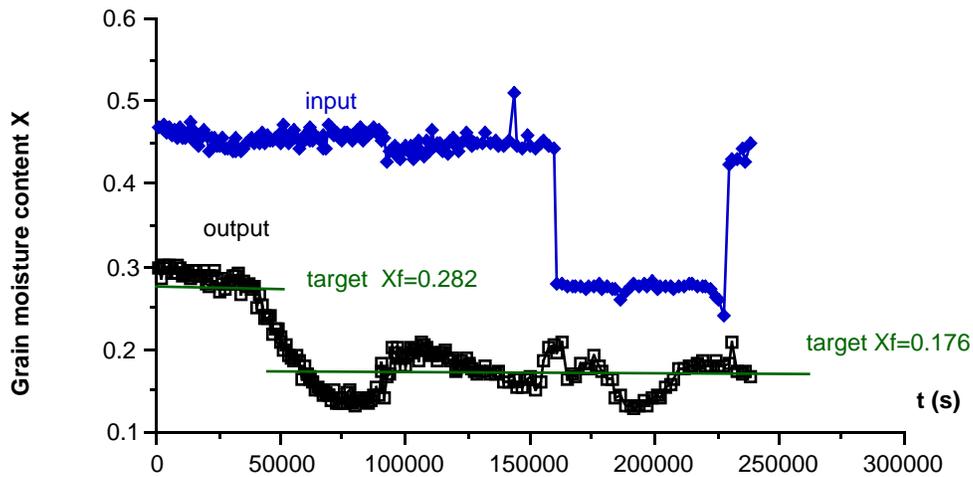


Figure 4.23: Test of the controller by experimentation : change of setpoint then step change of wet grain moisture content (test 7 / 1990).

And one can think, on this subject, that the controller would have to minimize over-drying phases very damaging for the grain. The model allows the development and the test of this type of possible improvement.

The experiment shows (figure 4.24) that there exists a very good correlation between wet-milling quality and moisture content of the dried grain. This may allow, for no additional cost, a real time estimation of the wet-milling quality of the dried corn, by the computer.

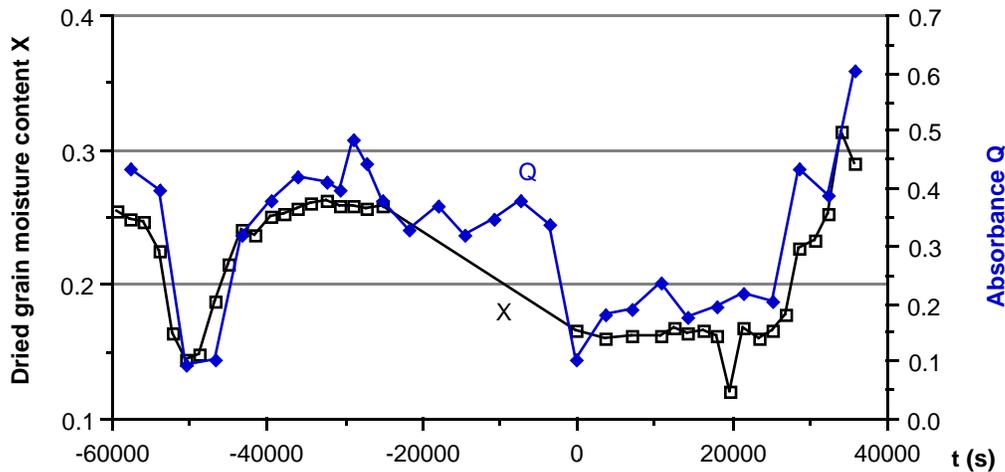


Figure 4.24: Experimental correlation between moisture content X and wet-milling quality Q of the dried grain (test 8 / 1990).

In practice, many other functionalities can be added to the controller (COURTOIS, 1990):

- failure diagnosis,
- fire alarms, security procedures,
- "real time" energy balances,
- remote control...

4.2.4 Conclusion

Through the use of the AFRC's algorithm, the potentialities of the dynamic model, used to simulate the unsteady-state behavior of the dryer, have appeared numerous.

Simulations agree well with experimentations, at least qualitatively. It would be suitable, however, to use a more powerful workstation to verify precisely this agreement.

Technological problems linked to the choice of sensors influence strongly the overall performance of the controller so that they should be chosen with care.

Moreover, in the future, the problem of the quality should be systematically taken in account during the design of a new algorithm.

Despite its lack of robustness and anticipation, the tested controller has seemed sufficiently performing for most uses.

The future belongs probably to adaptive controllers which take into account the moisture content of the wet grain.

Conclusion

Our purpose was to design, test and validate a dynamic model of corn drying adapted for mixed-flow dryers, majority type in France, and that is:

- to be implemented on a personal computer,
- to simulate the drying of grains in all transitory conditions: jump of air temperatures, drying, relaxation or cooling,
- to simulate, additionally, the degradation of the wet-milling quality,
- to simulate dryers with air recirculation,
- to predict the steady-state of a dryer in a few minutes, with a good precision,
- to simulate the dynamic behavior of a disturbed dryer, that it is controlled or not.

In brief, we were concerned with the development of a tool for static or dynamic optimization, design, setting and control of dryers. The model had to allow, in addition of the classical production capacity, energy consumption and product moisture content, to take into account the quality factor.

Problems of air and grain flow intervene, in fact, at the simplifying hypotheses and existing data level. The model does not allow therefore to distinguish the influence of air duct geometry and arrangement. It is the only way to simplify the model sufficiently to implement it on a microcomputer.

The choice of a dynamic model has been found justified at several levels:

- a classical model can not account for the drying acceleration after relaxation for example,
- at the level of the industrial dryer, the corn sees its drying air characteristics changing at each extraction: this is why, at the grain level, the drying regime can be qualified of unsteady state,
- for these two reasons, only a dynamic model can give a valid prediction of the wet-milling quality of the dried corn,
- only a dynamic model allows to study the dynamic behavior of the dryer (to develop a regulation).

The structured (and progressive) approach, from a corn grain submitted to a thermal stress to a controlled dryer, has allowed to validate the model, at each stage.

A quality equation has been defined in chapter 1. It presents an average precision for the user due, partly, to the "turbidity test" himself as well as to the two atypical campaigns that we have undergone.

A dynamic model of the thin layer corn drying has been developed (chapter 2). With an adjustment limited to two exchange coefficients and one transfer coefficient, on the kinetics under constant conditions dating 1980, the model was able to simulate the kinetics under variable conditions and to predict the wet-milling quality of the dried corn with the help of the equation defined in chapter 1.

A rapid numerical method (chapter 3) allows to simulate the deep bed drying. Experimental and simulated results agree well without additional adjustments.

An extension of this method has been developed (chapter 4) to simulate the steady state of an industrial dryer. Despite all simplifying hypotheses, experimental and simulated results agree well, there again, and without any additional adjustments. The obtained precision on the grain moisture content can be improved only through some model parameter re identification in order to integrate the influence of the air ducts characteristics, and porosity variations (dependent on the drying, extractions...).

Finally, this model (chapter 4) has been used to study the dynamic behavior of the ITCF pilot plant and to build a control algorithm. Despite the limited number of realized simulations, one observes a good agreement between simulation and experiments.

Possible perspectives of our work are following:

- To use the resulting knowledge from chapter 1 quality experiments to initiate new dryer designs and settings.
- To determine optimal locations and sizes of tempering zones in a dryer. To evaluate their impact on the wet-milling quality and on the resulting gain in drying acceleration.
- To determine the optimal height, air flow rate, air temperature for each dryer deep bed.
- Globally, to study and optimize all design parameters of a dryer.
- Globally, to study and optimize all setting parameters of a dryer.
- To test and develop new designs of dryers.
- To develop and to test advanced control algorithms.
- To predict, in real time, the output corn wet-milling quality.

The model has already been used successfully to test a new dryer design aiming a better quality.

Some points of our work would be profitable to be further investigated:

- A limited experimental design, based on drying experiments in fluidized bed coupled to the PROMATEST, would allow a readjustment of the quality coefficient K_Q for a better precision. Those work could be done in cooperation with the team of STEINMETZ at the ENSIGC of Toulouse.
- A more elaborate study of the thin layer model should allow the optimization of the volumic ratios between the 3 grain compartments and then to replace T_a by T_g in the exponential relationship between B_2 and T_a . This may insure a better precision in the cooling case.
- Thick layer experiments should allow to readjust B_1 and B_2 coefficients in order to integrate transfers not taken in account (e.g. conduction...).
- A more elaborate study of various industrial dryer simulations should allow to find parameters (or freedom degrees) to integrate air duct characteristics. This should allow to join our work and these of ARNAUD and FOHR at the LET of Poitiers, and these of FLICK and CHAABOUNI at the CEMAGREF to Antony.
- Re program the dynamic model on a workstation to be able to develop an adaptive control algorithm with forward effect on the humidity of the input grain.

This last point is the object of a cooperation between the ENSIA and the ITCF, beyond this thesis. I can insure personally the work continuity on this chapter.

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