Szent István University

ANALYSIS OF THE DRYING PROCESS OF AGRICULTURAL MATERIALS IN THE CASE OF VARYING LAYER DEPTH

Thesis book of Ph.D. dissertation

Bihercz Gábor

Gödöllő
2006.

Ph.D. school

name: **Ph.D. School of Technical Sciences**

discipline: **Science of Agricultural Technology**

head: **Dr. Szendrő, Péter**
professor, doctor of Hungarian Academy of Sciences
Szent István University, Faculty of Mechanical Engineering
Institute of Mechanics and Machine Parts
Gödöllő

supervisor: **Dr. Beke, János**
professor, dean, head of Institute
Szent István University, Faculty of Mechanical Engineering
Institute of Process Engineering
Gödöllő

....	....
Approval of the head of Ph.D. School	Approval of supervisor

TABLE OF CONTENTS

NOTATION

Note	Description
c_p	isobar specific heat, kJ/kg K
d	diameter, m
D	number of unit layers, –
DM	mass of dry material, kg
G	specific mass flow, kg/m^{2}s
k	drying constant, 1/s
l	layer depth, m
MR	moisture ratio, –
m_u	mass of dried material in unit layer, kg
p	partial vapor pressure, Pa
$p_{ambient}$	ambient pressure, Pa
r	evaporation heat, kJ/kg
t	temperature, °C
v	flow velocity, m/s
X	moisture content, kg/kg
Y	time factor, –

Greek letters

Note	Description
α, β	constants
φ	relative humidity, –
Π	pressure factor, –
ρ	material density, kg/m^3
ρ_{bulk}	bulk density, kg/m^3
τ	time, h

Indexes

Note	Description
0	initial value
in	inlet
e	equilibrium
out	outlet
sat	saturation

1. PREMISES AND AIMS OF WORK

Drying is a necessary technology and a very energy-demanding process of produced animals and vegetables in the area of food processing, and this is a tool of finishing of semi-processed or processed goods. Taking the given conditions into consideration development of technology is necessary, which serves several aims being often in disagreement with each other (in terms of improvement of availability value, avoidance of artificial additives, energy optimization, reducing of other cost factors, etc.). Until now several scientific works has been published serving solution for one specific problem of practice. The main idiosyncrasy of these works is the difference between their methods and availability; hence these are unsuitable to give a uniform model for products with different physical-biological properties. It goes without saying, because circumstances of their birth as well as their aims differed very much. Computer support nowadays allows us to build a uniform model on the basis of the previously made researches and auxiliary measurement results that can simulate the drying process of some most important agricultural products.

Other possibility is the building of a visual model that helps our better understanding of the drying process by its visual appearance.

According to the above mentioned facts the main aims of my work are as follows:

- evaluation and summarization of the available publications in this topic through a uniform approach,
- determination of material and technology parameters (independent variables) as the main parameters of modeling,
- developing a model, which is formally unified in mathematics and simulates the drying process of agricultural product drying with high accuracy in wide validity range;
- carrying on measurements to appoint the domain and co-domain of product- and/or technology dependent parameters.

The topic of simulation of convective drying has huge extensive literature therefore its detailed analysis is impossible thus only the most important parts have been reviewed in this work.

2. MATERIALS AND METHOD

2.1. Preparation of the Convective Model Drying Equipment

The first step of my work was the planning of a convective model dryer that allows the user to carry on thin layer and deep bed drying measurements, too.

My planning method was as follows. The main part of the equipment is a high performance fan, which is able to blow thought deeper product layers ($h > 25$ cm) as well as to aerate thin layers with much lower air velocity, hence an electric motor drive with 5 kW performances has been chosen (Figure 2.1).

An air heater was used that warms up the air at the worst of 0 °C temperature and 2 m/s velocity to 100 °C temperature. In this reason air heater with three row electric heater rod was used with 800 W performances, hence the whole electric power demand of air heater unit is 14.4 kWh.

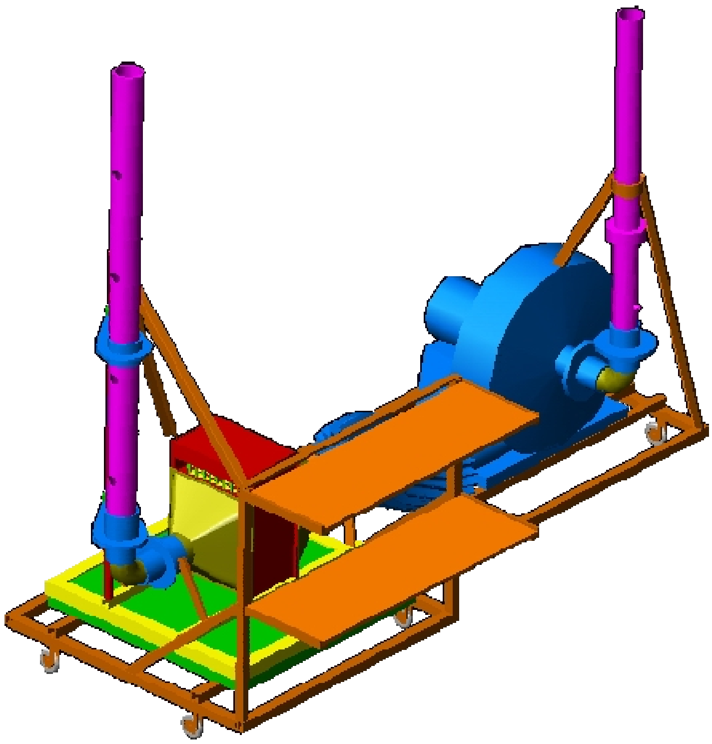

Figure 2.1 3D model of drying equipment

The volume flow of inlet air was measured with measuring flange (it has been prepared according to the related EU standards) with 4 different inner diameters. The sample holder is in direct connection with the air heater unit, hence heat loss is minimal. Below the sample holder a high precision BIZERBA type balance was installed that is able to display the weight decrease of the whole sample in 10 grams precision.

For the sake of the appropriate weight distribution a frame was designed on the balance, and to avoid the resonance of the fan unit these units were connected indirectly with a sail-cloth. Other advantages of this material are its air-proof property and the easy secure on the tube ends.

Appropriate frame system had to be planned to keep the whole measurement system. To keep the instruments, two wooden plates were planned, too. The fan unit as well as the air heater unit locates on separated dollies so these are easier to move.

One of the most problematic points of the design of the measuring equipment was the preparation of electric supply. At maximal load the necessary maximal current is 90A, which means 30A load on each phase, therefore 3 pieces of 32A fuse were applied in this case. Because of the huge electric current need a new electric system was built in the workshop.

From the fuses the 3 phase, the zero and earth were mounted into an electric clamp, where several outlet were built for the other electric consumers. Thereafter the electric circuit branches into two directions: the first one makes the supply for the electric motor of the fan of 5 kW performances and the second one supplies the air heater unit. Heating rods were controlled by a PLC unit located on the control box by the help of a 3 pieces of solid-state relay. Solid-state relays proved good during operation because of their extremely low dissipation and low heat generation; hence it could be installed in a closed control box.

Parallel to the high voltage circuit, it works a low voltage circuit, too, which supplies the PLC unit and the solid-state relays, where a 220V/5V converter was used located in the closed control box. This box was prepared according to the relevant standards of protection of electric shock.

2.2. Calibration of Measurement Equipment

By aerodynamic calibration of the measurement equipment a TESTO 454 type instrument was applied. The height of material column was changed between 0 cm to 175 cm in 25 cm steps and the velocity of the inlet and the outlet drying air were measured, furthermore calibration value was calculated by deduction of these two values. Difference between calibration values was not too high therefore I claimed that the equipment was tight enough. Determination of the exact value of the outlet air velocity was performed as addition of inlet the air velocity and the calibration values and was not measured during the tests any more.

In the measurement system Fe-CuNi thermocouples were used with the appropriate compensation lines. After the assembly of the measurement system the calibration of the thermocouples were carried out. In this case, the thermocouples and the data acquisition system were moved to the measurement place, therefore joint as well as other assembly failures were eliminated.

Iced water was used during calibration, which was stored in an appropriate sized pot where there was enough place for 8 more thermocouples, too. Water was getting warm and its temperature was measured by the thermocouples and a classic mercury thermometer, too. The difference between the values gives the calibration values for the temperature data.

In the measurements, the real values of the temperatures were calculated as addition of the measured temperature data and the appropriate calibration value.

2.3. The Method of Measurement

The building of the measurement system is to be seen in Figure 2.2. The ambient air is drawn by the fan through a measuring flange. The quantity of the inlet air is varied by an end cone adjusted manually; hence the outlet air velocity during drying could be kept quite constant. The value of the inlet air velocity was calculated by the help of the measuring flange.

The electric heater heats up the drying air to the aimed temperature, which had to set before the start of the measurement and this temperature is controlled by a PLC unit automatically. The weight of the air-heater unit with the sample holder was measured by a high precision balance, so the weight loss during drying could be checked.

Within the sample holder Fe-CuNi thermocouples were installed in 25 cm steps, and their data were gathered and stored by a JUMO type data acquisition equipment. The sampling time was adjusted to 5 minutes. These values were modified by adding the appropriate calibration values.

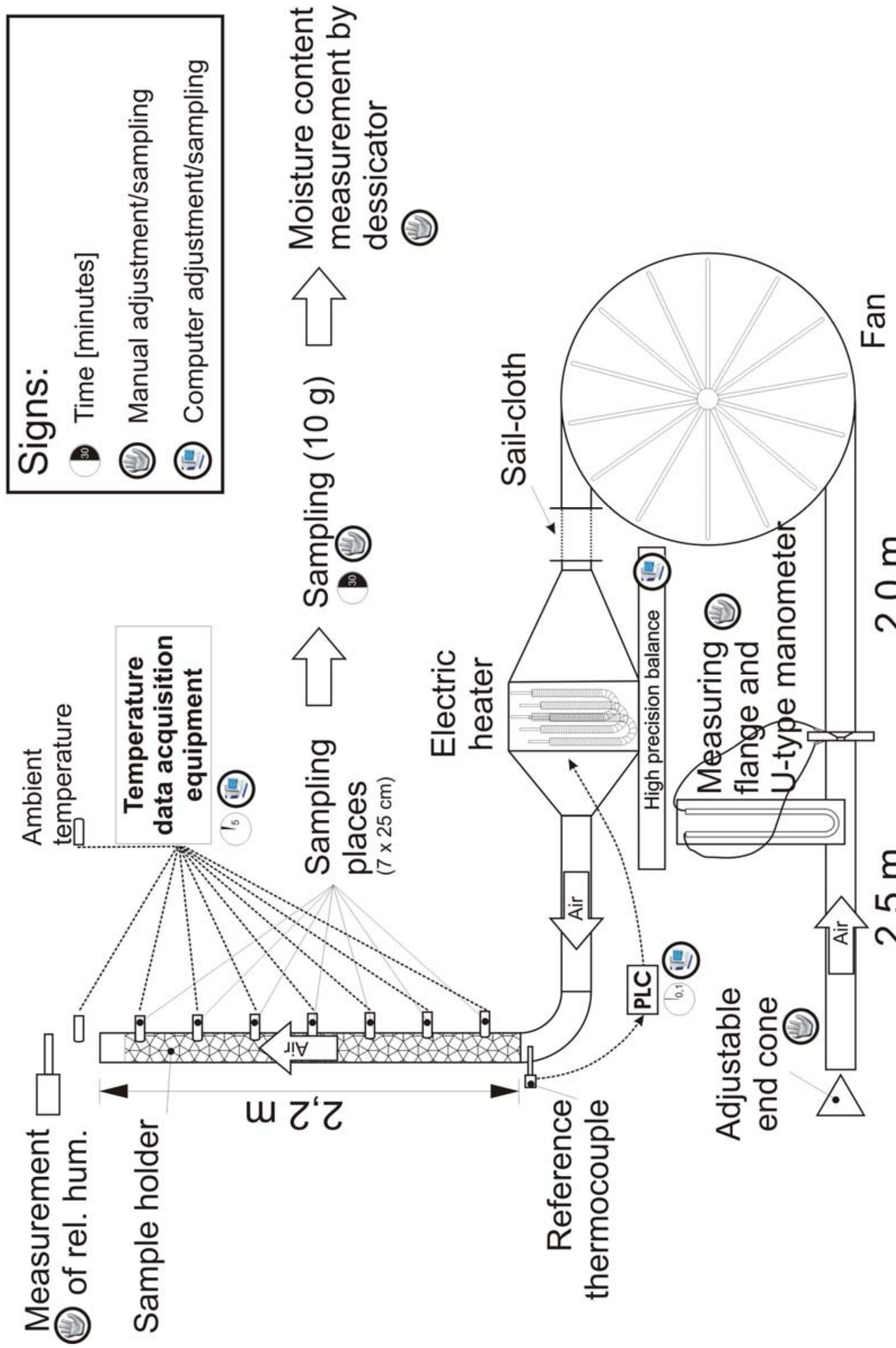

Figure 2.2 Assembly of the measurement system and the measurement method

During operation, the material sampling was carried out by unplugging the rubber plugs with the thermocouple and taking 10 grams sample from each sampling hole in every half or one hour. The moisture content of the samples was analyzed by a dessicator. The relative humidity and velocity of the outlet air was measured by a TESTO 454 instrument right before sampling.

The real model dryer and instruments is to be seen in Figure 2.3.

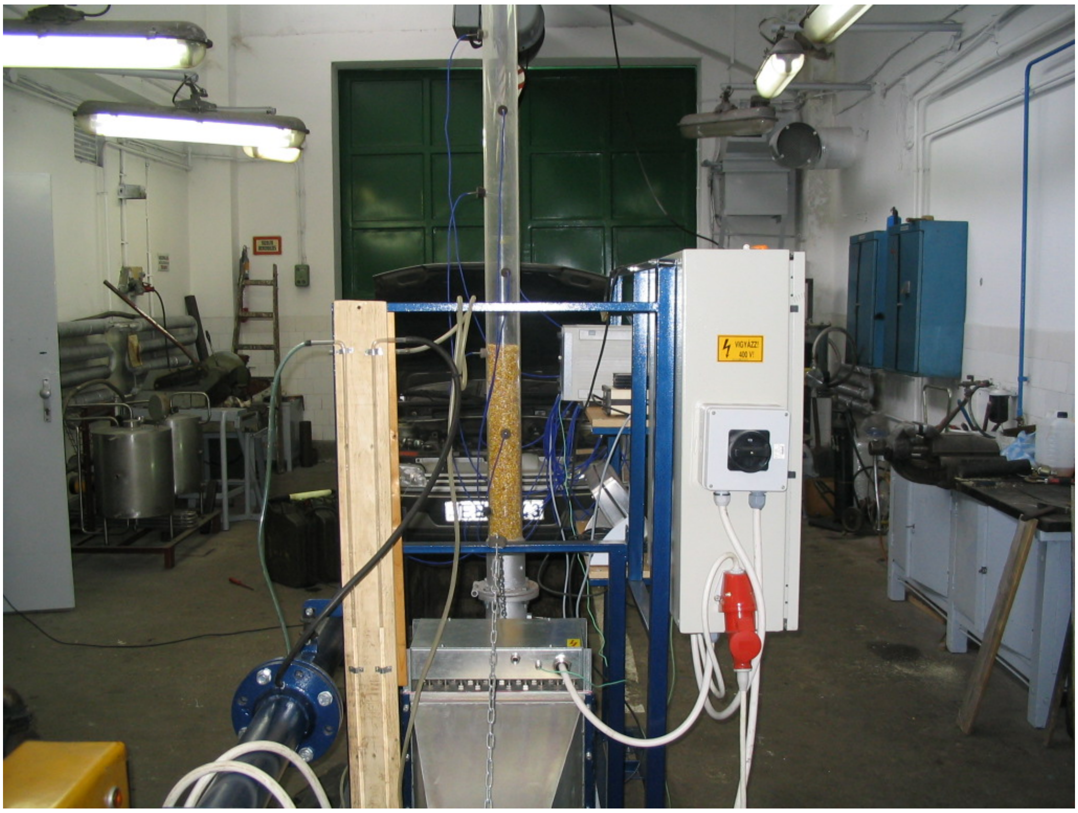

Figure 2.3 The real measurement system from the view of fan unit

3. RESULTS

3.1. Evaluation of the measurement data

In case of convective drying the dewatering process of thin layer drying can be described mathematically very well on the basis of the instantaneous temperature- and moisture content of the dried material and the drying air.

The accuracy of semi- or whole empiric models of deep bed drying process of agricultural materials depends on diffusion factors in functions of the material properties and the effect on water removal.

Basic equation of logarithmic and semi-empiric model of Hukill is as follows:

$$MR = \frac{2^D}{2^D + 2^Y - 1} \tag{3.1}$$

where D is the number of unit layers[1], $Y = \tau/\tau_{half}$ time factor and τ_{half} is the half time[2].

Drying rate of deep batches can be calculated in functions of the temperature decrease of the drying medium within the unit layer (Δt_{air}), the increase of the temperature of the dried product within the unit layer ($\Delta t_{material}$), the specific mass flow of the drying medium (G_{air}) and some physical properties of the dried material as follows:

$$\frac{dX}{d\tau} = \frac{G_{air} \cdot c_{air} \cdot \Delta t_{air} - c_{material} \cdot \Delta t_{material}}{r_{water} \cdot \left(X_{material_0} - X_{material_e}\right)} \left[\frac{kg}{h}\right] \tag{3.2}$$

In this method, the whole batch was simulated as several thin layers on each other, and the parameters of the outlet drying air of one unit layer are the parameters of the inlet drying air of the next unit layer. The mass of a unit layer (m_u) can be determined by the help of the Hukill-type half time (τ_{half}) and the drying rate ($m_u = \tau_{hr} \cdot dX/d\tau$). According to the above mentioned facts the number of unit layers can be calculated as follows:

$$D = \frac{l \cdot \rho_{material} \cdot r_{water} \cdot \left(X_{material0} - X_{material_e}\right)}{G_{air} \cdot c_{p_{air}} \cdot \tau_{half} \cdot m_u \cdot (t_{air} - t_{material})} \; [-] \tag{3.3}$$

The kinetic curves of drying could be calculated by the help of the equation of moisture ratio [$MR = (X\text{-}X_e)/(X_0\text{-}X_e)$], but it does not take into consideration the effect of different initial moisture content of the dried material, and the drying

[1] A layer has unit depth if it dries simultaneously in time.
[2] Half time is the time, during it the product loses half its moisture content to be removed.

kinetic curves of the dried material in case of deep bed drying and they have to be known before the simulation. At the beginning of stationary deep bed drying (depending on the properties of the drying medium and the applied batch height) rewetting may occur. Primary reason of this phenomenon can be the relative high initial moisture content of the dried material and the impregnation of the drying medium; hence the drying rate curves could have negative values in this range. The real drying occurs after the evaporation of the condensed water in the unit layer. After plotting the drying rate values in function of moisture ratio values, the start point of real drying can be determined: increasing the whole layer depth, the maximal drying rate moves toward the lower moisture ranges. A similar phenomenon can be experienced by decreasing the temperature of the drying medium.

The second based or classic Hukill model does not take the drying ability of flowing medium through the layer into consideration, therefore it gives a wide approach to the real process.

When the temperature of the drying medium becomes low the dew point temperature water condenses in the layer and the partial vapor pressure of the outlet drying air will be equal to the saturation vapor pressure. In this case, the partial vapor pressure of the drying air has important role in the drying process.

To avoid the above mentioned failure the following pressure factor (*Π*) should be applied:

$$\Pi = 1 - \frac{p_{sat_{in}} - p_{out}}{p_{sat_{in}} - p_{in}} \quad [-] \tag{3.4}$$

where p_{in} is the partial vapor pressure of the inlet drying air, p_{out} is the partial vapor pressure of the outlet drying air, $p_{sat\ in}$ is the saturated partial vapor pressure of the inlet drying air.

The original Hukill equation is valid if $\Pi \to 0$, hence $(p_{in}-p_{out}) \to 0$ must be true. Therefore instantaneous values of moisture ratio have to be taken into consideration to be able to generalize the original Hukill equation, so it gives the possibility to show the effect of rewetting:

$$MR = \frac{2^D + 2^\Pi - 1}{2^D + 2^Y - 1} \tag{3.5}$$

The moisture ratio of equation (3.5) gives a good approach to the real values calculated by the measurement data. This method has appropriate accuracy and it is quite simple to use easy in the practice of simulation of deep bed drying in case of different drying air temperature and layer depth.

On the other hand the value of moisture ratio can be calculated by other methods, as well, and the most often used ones are as follows:

1. *Flood*-type equation:

$$MR = e^{-k \cdot \tau^{\alpha}} \tag{3.6}$$

where **k** and **α** are constants, **τ** is the time in hours.

2. *2nd and time based Hukill* model:

$$MR = \frac{2^{k \cdot \tau^{\alpha}}}{2^{k \cdot \tau^{\alpha}} + 2^{k \cdot \tau^{\beta}} - 1} \tag{3.7}$$

where **k**, **α** and **β** are constant, **τ** is the time in hours.

3. *2nd based modified Hukill* model:

$$MR = \frac{2^{D} + 2^{\Pi} - 1}{2^{D} + 2^{Y} - 1} \tag{3.8}$$

4. *Exponential based modified Hukill* model:

$$MR = \frac{e^{D} + e^{\Pi} - 1}{e^{D} + e^{Y} - 1} \tag{3.9}$$

I made the validation of equations (3.6-3.9) by the help of my own measurement data and I made the modeling by MATLAB SIMULINK program.

On the basis of drying rate calculated by the moisture content data average deviations was determined and I clamed that all methods, except the Flood theory (3.6 equation), are within the 5% failure limit. Under the other three methods the exponential based Hukill method (equation 3.9) gave the most accurate results therefore this theory was used in my future work.

3.2. The simulation model

Before running the MATLAB SIMULINK model some settings must be done. This means that some constant has to be set and some constant-dependent functions have to be calculated, which do not vary during simulation.

The basic constants of the simulation model are as follows:

- initial relative humidity of the inlet drying air ($\varphi_{air\ 0}$, %);
- initial temperature humidity of the inlet drying air (t_{air}, °C);
- velocity of the inlet drying air (v_{air}, m/s);
- initial moisture content of the dried material ($X_{material\ 0}$, kg/kg);
- initial temperature of the dried material ($t_{material\ 0}$, °C);
- whole layer depth (l, m);
- ambient pressure ($p_{ambient}$, Pa);
- diameter of drying chamber (d, m);
- specific heat of water (c_{water}, kJ/kgK).

The variables of the model are as follows:

- number of the unit layers (D, -);
- specific heat of the drying air (c_{air}, kJ/kgK);
- half time (τ_{half}, h);
- density of the drying air (ρ_{air}, kg/m^3);
- bulk density of the dried material (ρ_{bulk}, kg/m^3);
- equilibrium moisture content of the dried material ($x_{material\ e}$, kg/kg);
- specific heat of the dried material ($c_{material}$, kJ/kgK);
- partial vapor pressure of the drying air (p_g, Pa);
- saturated partial vapor pressure of the drying air ($p_{sat\ g}$, Pa);
- instantaneous relative humidity of the drying air (φ_{air}, %).

The drying time of convective deep bed drying can be calculated by the Hukill method:

$$\tau_{Hukill} = \frac{DM \cdot r_{water} \cdot \left(X_{material_0} - X_{material_e}\right)}{G_{air} \cdot \rho_{air} \cdot c_{p_{air}} \cdot \left(t_{air_0} - t_{material_0}\right)} \ [h] \tag{3.10}$$

I decided to make BUS lines as inputs and outputs in the model, because a lot of connection lines had become redundant so the model is much better to understand. The input BUS contains the following data in the following order:

1. number of the unit layers (ERS);
2. relative humidity of the drying air entering the unit layer (fi);
3. drying air temperature entering the unit layer (t).

There are two output BUS lines in the model, which seem to be unnecessary because the second one contains all the data of the first one. The difference is the following: the first BUS serves the direct data transfer between "deep bed blocks", the second one serves the diagnostic aims and here you can check the model values of each SIMULINK block. The second BUS transfers the following data (and the first BUS transfers just the first three data member of the second one between the blocks):

1. number of the next unit layer (ERS);
2. relative humidity of the drying air leaving the unit layer (fi_l);
3. temperature of the drying air leaving the unit layer (t_l);
4. moisture content of the drying air leaving the unit layer (x_l);
5. temperature of the dried material in the unit layer (t_a);
6. moisture content of the dried material in the unit layer (x_a).

According to the above mentioned facts, the SIMULINK model of convective deep bed drying can be built as it can be seen in Figure 3.1.

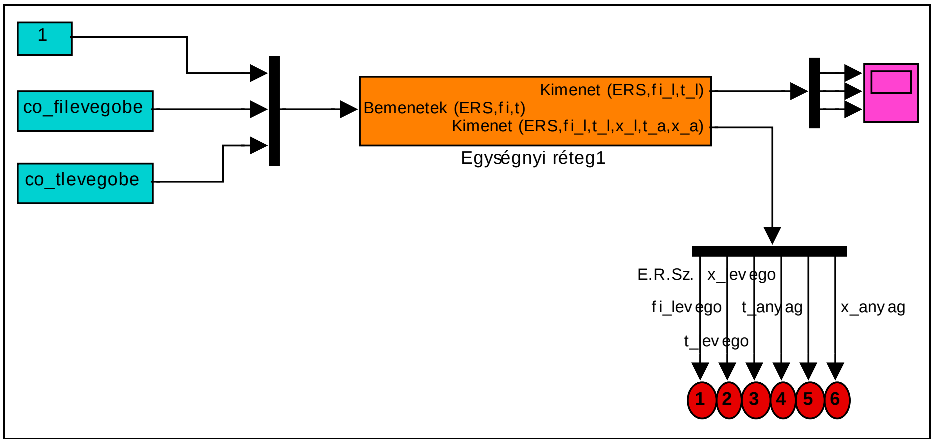

Figure 3.1 The MATLAB SIMULINK block for simulation of convective deep bed drying

Before staring the simulation the number of unit layers has to be calculated then "deep bed blocks" (see Figure 3.1) must be copied in the number of its value. After copying the blocks must be connected by BUS lines. In this way model with optional number of unit layers can be built, but it must be in view that each new block raises the calculation time, exponentially; hence it is not worth copying these blocks in huge amount.

3.3. Simulation Results of Corn Kernels

The previously described moisture ratio (3.9 equation) can be calculated by constant Π pressure factor (Figure 3.2), and on the basis of this curve the drying rate curves can be calculated, as well (Figure 3.3).

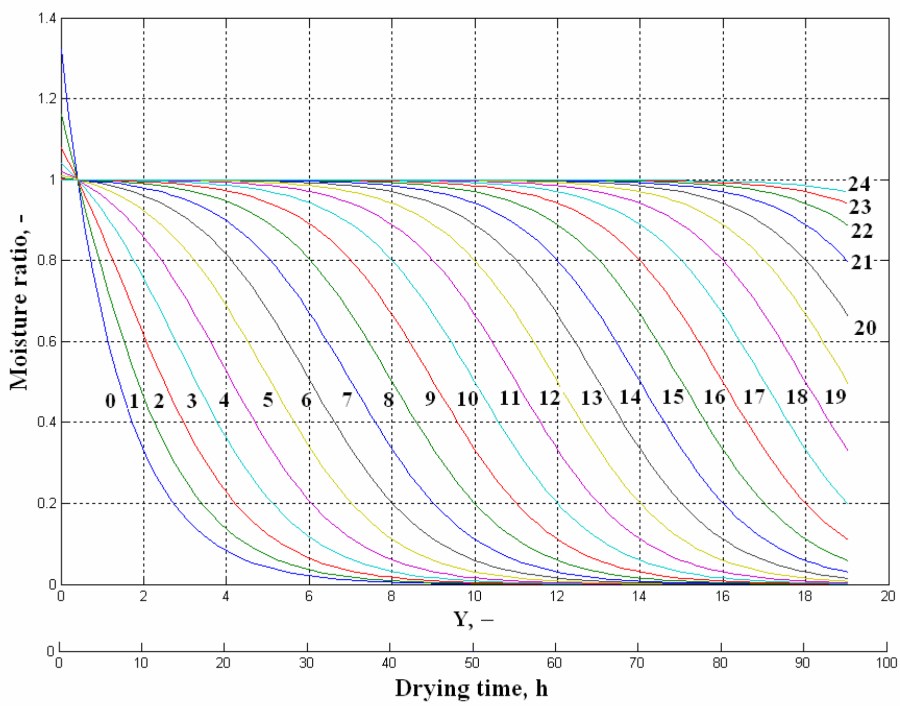

Figure 3.2 Modified moisture ratio (MR) curves calculated with constant Π pressure factor in function of the drying time/time factor (Y)
(Numbers on each curve show the number of the unit layer counted from the air inlet.)

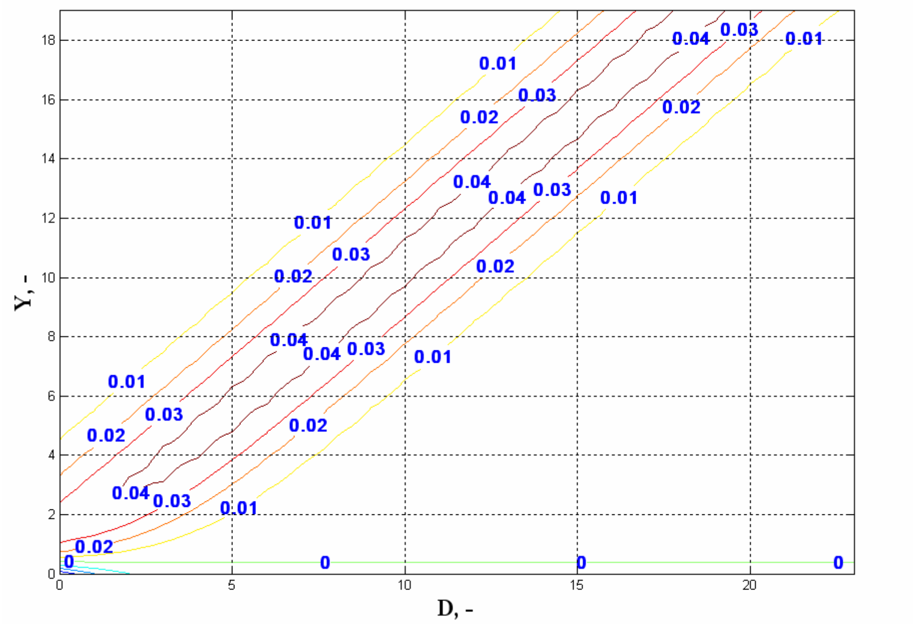

Figure 3.3 Drying rate curves calculated by the moisture ratio curves (Figure 3.2) in functions of the time factor (Y) and number of unit layers (D)
(Numbers on each curve show the value of the drying rate in kg/kgh)

On the basis of the moisture ratio values the moisture content of the dried material can be calculated where the initial moisture content of the dried material must be considered. As a general case, the initial moisture content was set 0.33 kg/kg and the change of the moisture content in function of the drying time can be seen in Figure 3.4. The figure shows that the current 2 m height layer by this general settings contains 7 unit layers altogether. The moisture content of the dried material in the unit layer being the closest to the inlet air cross section decreases rapidly at the beginning of drying and then it comes to a constant value (equilibrium moisture content calculated by properties of the inlet drying air). The moisture content of the second unit layer shows the effect of rewetting already at the very beginning of the drying and then its value decreases exponentially towards the equilibrium moisture content. By growing the number of unit layer raises the effect of the initial rewetting and the maximal moisture content values of each unit layer. It is getting higher towards the outlet cross section. Furthermore, the higher the unit layer is the later the rewetting begins.

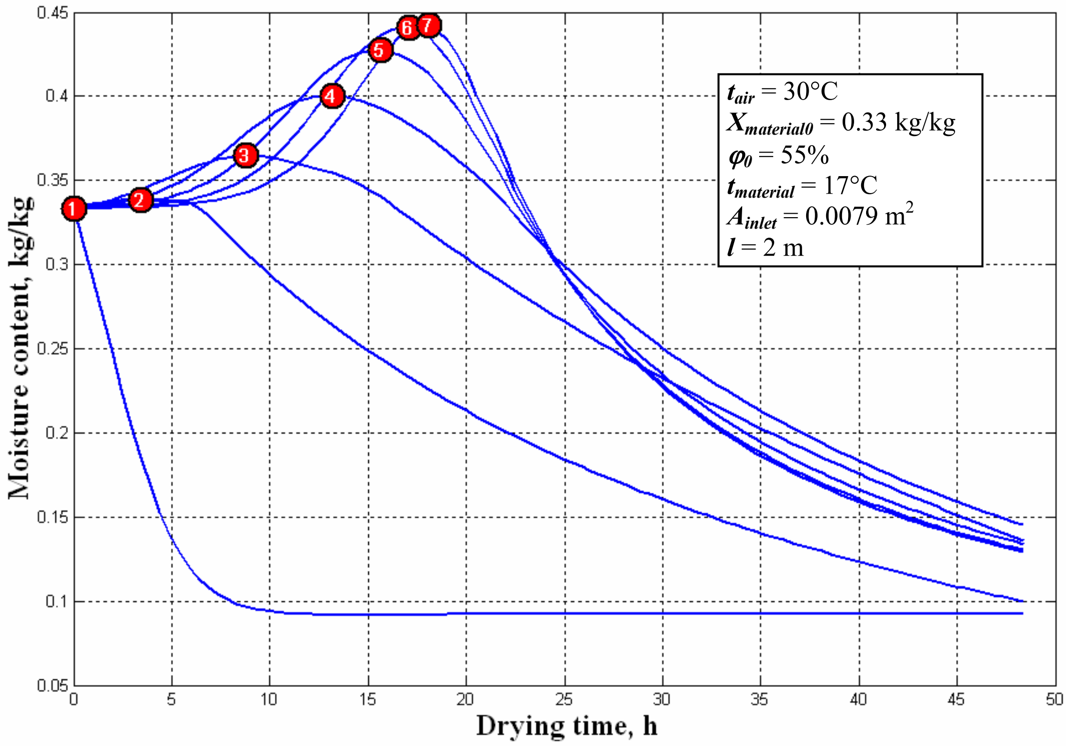

Figure 3.4 Moisture content curves in function of the drying time in the case of convective deep bed corn drying

(The numbers in the maximum points of each curve shows the number of the unit layer counted from the cross section of the air inlet.)

Figure 3.4 shows that the curve of maximum points of moisture contents is not a linear function of the drying time and the layer depth. If the maximum moisture content points are drawn in functions of the drying time and the layer depth, then it would show a 3D curve rising in every positive axis directions. The gradient factors of this curve would be the appropriate parameters of the dried material and the drying air as well as the drying technology.

Figure 3.4 shows unambiguously that the initial rewetting makes the drying process longer, therefore the Hukill-type drying time must be modified.

For the sake of more accurate analysis of this phenomenon I defined the "activation time", which is the duration between the starting time of drying and the point when the moisture content of the given unit layer reaches again the initial moisture content after rewetting. The modified Hukill method has the ability to predict the drying time just from the maximum moisture content point so the track of time of rewetting was neglected.

On the basis of the above mentioned facts the half of activation time was calculated by the help of moisture content curves as the duration between the maximum moisture content point and the point when the moisture content of the given unit layer reaches again the initial moisture content after rewetting (Figure 3.5).

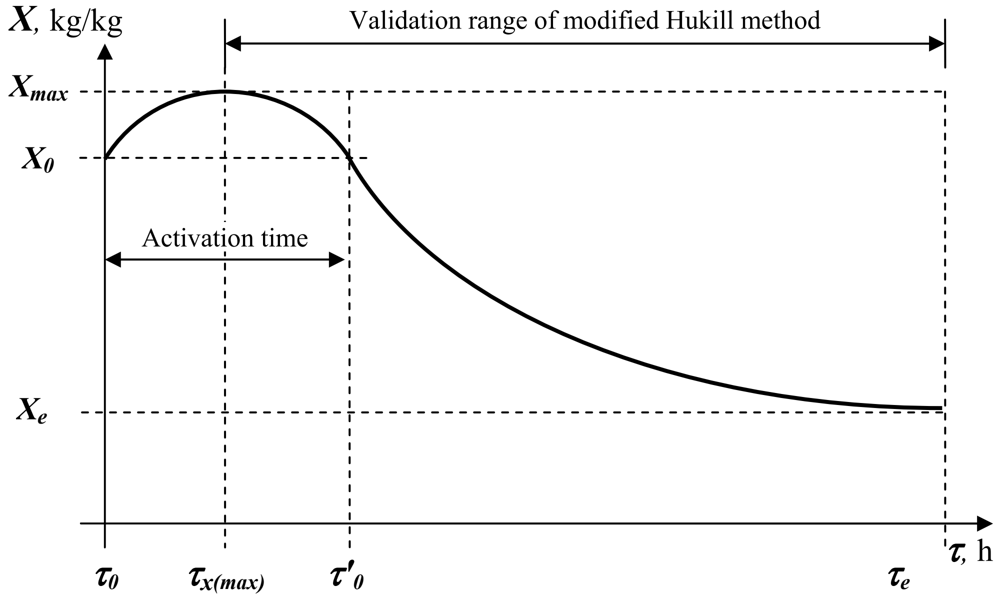

Figure 3.5 Calculation method of activation time

In this way, the whole drying time can be calculated more accurately with equation (3.11) then by the original Hukill method.

$$\tau = \frac{1}{2}\tau_{activation} + \tau_{Hukill} \; [h] \qquad (3.11)$$

Equation (3.10) can be substituted into the equation (3.11), so the equation of real drying time can be written as follows:

$$\tau_{Hukill} = \frac{1}{2} \cdot \tau_{activation} + \frac{DM \cdot r_{water} \cdot \left(X_{material_0} - X_{material_e}\right)}{G_{air} \cdot \rho_{air} \cdot c_{p_{air}} \cdot \left(t_{air_0} - t_{material_0}\right)} \ [h] \tag{3.12}$$

I calculated the activation times by the help of equation (3.12) in case of varying layer depth. According to the results (see Figure 3.6) it can be claimed that by the given technology and material conditions rewetting occurs above 1.25 m layer depth. If the drying technology allows using lower layer depth than this value then rewetting could be avoided otherwise rewetting at higher layers must be treated. On the basis of the calculated activation time it can be claimed that in case of use of drying air with 30°C temperature the whole drying time will be 4 hours longer than it had been predicted until this time.

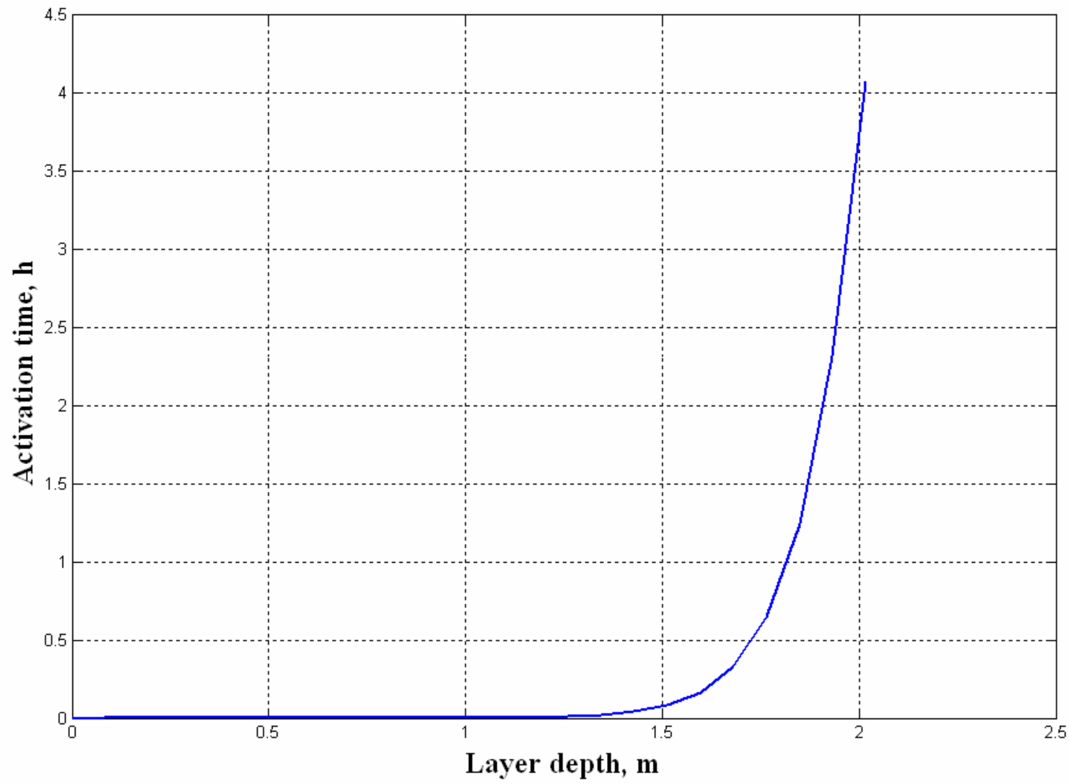

Figure 3.6 Activation time of corn kernels in different layer depth

The activation time can be calculated by the help of the initial moisture content of the dried material and the layer depth, which shows that by increasing the value of moisture content and layer depth the activation time increases, too.

Coherence between activation time and the temperature of the drying air can be showed similarly way than the previous one. By decreasing the temperature of the drying air and increasing the layer depth the activation time increases, too. Deeper layer bed results in stronger rewetting at higher levels of the dried batch.

3.4. Recommendation for modeling of the drying process of stringy fodders

Drying process of stringy fodders differs in several views from that of kernels, but this model gives a good approach for the description of the drying process of stringy materials, too. More accurate determination of all the variants need more measurements but the measurement data I have is sufficient to show the model's ability for simulation of the drying process of alfalfa.

In this case, the model discussed in the previous chapter had the following settings:

$\boldsymbol{X_0}$ = 1,78 kg/kg;
$\boldsymbol{X_e}$ = 0,163 kg/kg;
$\boldsymbol{\rho_{material}}$ = 148,15 kg/m^3;
$\boldsymbol{l_{batch}}$ = 1 m;
$\boldsymbol{\varphi_{air}}$ = 60%;
$\boldsymbol{t_{air}}$ = 30°C;
$\boldsymbol{t_{ambient}}$ = 17°C;
$\boldsymbol{p_{ambient}}$ = 102 400 Pa.

The shape of the moisture ratio curves in case of alfalfa drying is similar to that of corn kernels, but the result is adapted to the shorter drying time (Figure 3.7). This figure shows the effect of the initial rewetting at the beginning of drying in the higher levels of batch of the dried material. The maximum moisture content of the dried material exceeds by 32% its initial value.

On the basis of the moisture ratio curves the moisture content curves can be calculated (Figure 3.8), which have similar shape to that of corn kernels except their revealing limits.

Drying rate values of alfalfa are higher than drying rate values of corn kernels which are caused by the different texture of the two kind of vegetables. The maximum value of the drying rate of corn kernels is about 0.05 kg/kgh, and that of alfalfa by similar setting is about 0.1 kg/kgh. It means that the drying rate is doubled for alfalfa.

In the case of the applied settings the whole drying time of alfalfa is about 54.4 hours which is modified by 1.7 hours activation time if the layer depth is 1.3 meters. The varying of the activation time in function of the layer depth is similar to that of corn kernels: increasing layer depth causes increasing activation time but rewetting does not occur under 0.8 meter layer depth.

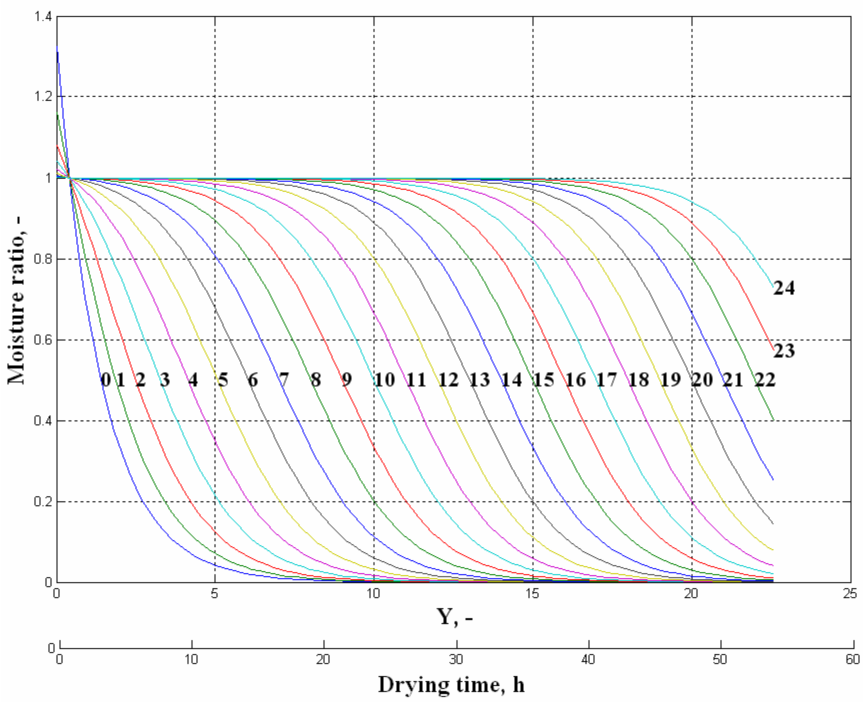

Figure 3.7 Modified moisture ratio (MR) curves by constant Π pressure factor in function of the drying time/time factor (***Y***)

(Numbers on each curve show the number of the unit layer counted from the air inlet.)

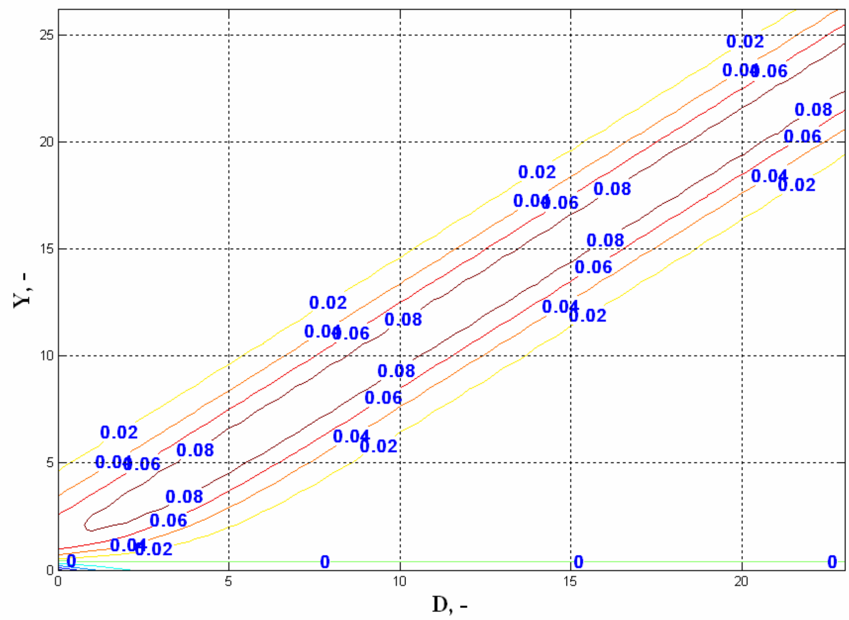

Figure 3.8 Drying rate curves calculated by the moisture ratio curves (Figure 3.6) in functions of the time factor (***Y***) and number of unit layers (***D***)

(Numbers on each curve show the value of the drying rate in kg/kgh)

4. SUMMARY

4.1 Summary of research activities

Several scientific works have been published in the literature on sorption and desorption isotherms of biological products. Some of these give a good description about watering and dewatering processes of drying products. Application of these methods can be carried out with a given precision and its validity is sometimes very limited in view of the range of moisture ratio and temperature. Furthermore, practical failures and the above mentioned disadvantages limit the determination of equilibrium moisture content. On the basis of this fact, the most appropriate solution for this problem may be the use of pure empirical models. Literature suggests that mainly polynomials fit to the measurement data.

Thin layer drying models could be good tools in determination of deep bed drying processes. Diffusion equations give detailed information about moisture- and temperature distribution within the grain kernel. By the use of deep bed drying models, the determination of some drying parameters could be enhanced at a given layer depth and drying time. These models require initial and boundary conditions, which take the shape of single kernel, its mass diffusion and thermal conductivity into consideration. In this case the most time demanding step within the whole calculation method is the above mentioned fact, which is a big disadvantage of this method.

One of the main aims of my work is the analysis of phenomenon of rewetting in case of deep bed drying. Literature does not contain any solution for this problem, or just some with very limited validity range. I prepared a new model-drying equipment to be able to analyze the phenomenon of rewetting. I made the design of this equipment in AutoCAD and I have built 3D models as large as life and the realization of the drying equipment was carried out by these plans. Calibration and installation of the measuring instruments were made by myself, and I prepared the measurement row, too. The whole system works with electric power because it is easy to handle, but setting up the electric system is rather troublesome.

I chose the half empirical and logarithmical method to prepare the layer-independent drying model, which has relative low mathematical background. Modification of Hukill method [BEKE et al., 1994] allowed us to analyze the effect of rewetting under deep bed drying; therefore description of the drying process can be more realistic. On the basis of my own measurement data I realized, that the base of 2 in case of the original Hukill method can be changed to exponential base, so the precision of the model could be enhanced (confidential analysis of the four analyzed model gave the best result in case of exponential-based Hukill method). I made the appropriate MATLAB SIMULINK models according to the modified exponential based Hukill method, and I prepared my own toolbox for simulation of layer-independent drying process. After setting of basic parameters for a general case I built up the appropriate SIMULINK model and moisture ratio (MR) curves were drawn. These MR curves apparently show the effect of rewetting, namely the value of some curve exceeded the value of one. Furthermore, change of moisture content of the dried material (here dent corn as a determinative sort of grains) during drying was calculated and recommendation for setting this model for alfalfa was written, as well. Rewetting makes the drying time longer; I defined this extra time over the original drying time as “activation time”. By warm air drying (30-40°C) of corn kernels the activation time is 2 and half higher than in case of alfalfa drying with the same model settings.

Activation time and degree of rewetting are very important parameters of the given drying technology. Taking these factors into consideration, operation of drying equipment can be optimized.

4.2 New scientific results

1. I developed a SIMULINK-based model for simulation of the drying process of some agricultural products by varying parameters of drying technology as well as that of dried materials. The developed model is capable of determining the most important factors of convective drying (such as height of unit layer, height of drying zone, probable drying time, etc.). This model has the possibility to compare several logarithmical half-empirical simulations, too.

2. I worked out a new method for determination of „moisture ratio-drying time-layer depth” values of agricultural products dried in different layer depth. I claimed that local rewetting occurs at the beginning of drying above a certain layer depth according to the parameters of the applied drying technology and dried material. Taking the effect of rewetting into consideration, the pressure factor (***Π***) can be determined as function of the partial vapor pressure of inlet drying air ($\boldsymbol{p_{in}}$), partial vapor pressure of outlet drying air ($\boldsymbol{p_{out}}$) as well as saturated vapor pressure of inlet drying air ($\boldsymbol{p_{sat\ in}}$), respectively. In this way, the moisture ratio of Hukill model can be modified as follows:

$$MR = \frac{e^D + e^{\Pi} - 1}{e^D + e^Y - 1}$$

   The results of this method give the most accurate values for moisture content of the dried material. The model is able to predict the maximum values of moisture content of dried material after rewetting, and the number of the rewetted unit layers. In this way the maximum points show the start of drying and time values of these points give the delay of the whole drying time.

3. I defined the activation time (τ_a), which gives a time delay value between the start of drying and the end of rewetting. This time factor is neglected by other calculation methods. I claimed that moisture content curves are symmetrical to the y-axis moved to the maximum moisture content point, hence time section between the start of drying and maximum rewetting point is equal to the time section between the maximum rewetting point and the point when moisture content of dried material reaches its initial value again (Figure 3.5). On the basis of the above mentioned facts, a modified drying time equation of Hukill can be determined as follows:

$$\tau_{Hukill} = \frac{1}{2} \cdot \tau_{activation} + \frac{DM \cdot r_{water} \cdot \left(X_{material_0} - X_{material_e}\right)}{G_{air} \cdot \rho_{air} \cdot c_{p_{air}} \cdot \left(t_{air_0} - t_{material_0}\right)} \; [h]$$

   which enables us to calculate the drying time more accurately. I showed that activation time is primarily the function of layer depth, initial moisture content of dried material and the temperature of the drying air.

4. I showed that the texture of agricultural materials determines the value of activation time, which could be the consequent of water bound energy. I claimed that in case of similar initial conditions of drying technology the activation time of stringy materials is about 2.5-times higher than that of kernels.

4.3 Practical application of scientific results

Modeling with MATLAB SIMULINK program is a widespread method for simulation of several kinds of processes, but practical research and development of an own model could result several awkwardness, possibly. This requires substantial knowledge of functionality of the program and sometimes the possibility of graphical programming is not able to fulfil all the requirements of a problem like this, therefore code area must be used, as well. The last mentioned fact could render it more difficult during research except when the user is an advanced master of C-program languages, because MATLAB program language is one kind of this. Avoiding the classical type-written programming and in this way the use of graphical programming could reduce the load of the researcher, who would have more time to solve his/her actual problem without entering the details of computer programming. My SIMULINK toolbox is a useful tool to avoid the above mentioned problem and make models easy and quick.

Simulation of change of moisture content within the batch in case of convective stationary bed drying during drying time can be carried out by the Hukill method modified by myself, and change of moisture content depends on several properties of the current drying technology. By the help of this method there is the possibility to set up the parameters of drying technology so it allows avoidance of the appearance of rewetting at higher level of grain batch during drying. Firstly model parameters depending on technical data of drying equipment must be modified (e.g. diameter of drying equipment), then according to the variable settings of dryer new model inputs must be prepared and the optimal settings will be the same without rewetting. By the help of my method the necessary parameters can be predicted and the drying process can be optimized.

Second factor resulted in by the rewetting is the activation time. This extra time is necessary because of initial rewetting of deep beds during drying, because some part of grain batch must be dried down from higher moisture content than the initial. Therefore drying time of the tested dryer must be extended by the activation time (with the half of the activation time, namely, according to the 5.2 equation). On the basis of the above mentioned fact, it can be determined, that the degree of rewetting as well as the value of activation time are both very important factors of the drying process, which helps us to determine the drying time more accurately than before and to optimize the operation of the given drying plant.

In my dissertation I managed to show that the morphology of vegetables exerts high influence on the water removal process, therefore in the view of the drying technology the physical-biological properties of a dried material are very important. The best solution would be the use of vegetables with quite quick water removing properties, which could be a grateful task for vegetable ennoblers.

5. PROFESSIONAL PUBLICATIONS

Proceedings in Hungarian

1.1. Beke, J.; **Bihercz, G.***: A mikrohullámú gabonaszárítási folyamat egyes jellemzői az elektromágneses paraméterek függvényében. In: *4. Magyar Szárítási Szimpózium Proceedings Kiadványa*, pp. 22, Mosonmagyaróvár, 2001.

1.2. **Bihercz, G.***; Beke, J.: Kísérleti eredmények elemzése rétegvastagság független szárítási modell kifejlesztéséhez. In: *MTA-MÉM Kutatási Tanácskozás Kiadványa* 26. Kötet, Gödöllő, 2002

1.3. **Bihercz, G.***; Beke, J.; Kurják, Z.: Leveles zöldségek konvektív szárítása. In: *MTA-MÉM Kutatási Tanácskozás Kiadványa* 27. Kötet, Gödöllő, 2003

1.4. Kurják, Z.*; Beke, J.; **Bihercz, G.**: Egyes zöldségfélék száradási tulajdonságainak vizsgálata mikrohullámú térben. In: *MTA-MÉM Kutatási Tanácskozás Kiadványa* 27. Kötet, Gödöllő, 2003

1.5. **Bihercz, G.*;,** Kurják, Z*: Egyes eltérő fizikai tulajdonságú zöldségfélék száradási jellemzőinek vizsgálata. In: *5. Magyar Szárítási Szimpózium Proceedings Kiadványa*, pp. 5-14, Szeged, 2003

1.6. Beke, J.; **Bihercz, G.;** Kurják, Z.: Petrezselyemzöld száradásának összehasonlító vizsgálata. In: *MTA-MÉM Kutatási Tanácskozás Kiadványa* 28. Kötet, pp. 12, Gödöllő, 2004

Other Hungarian issues

2.1. **Bihercz, G.:** A dehidrációs folyamat analízisén alapuló rétegvastagság-független szárítási modell kidolgozása egyes mezőgazdasági terményre, In: *SZIE-Műszaki Tudományi Doktori Iskola: Kutatási Beszámolók*, pp.33-38, Gödöllő, 2004

Proceedings in Foreign Languages

3.1. Beke, J. **Bihercz, G.***: Positioning Effects on the Moisture Movement in Maize Samples During Microwave Drying, In: *Proceedings of the 1st Youth Symposium on Experimental Mechanics* (ISBN 88-901080-0-2-44406), Bertinoro(Italy) – 2002, pp. 55-56.

3.2. **Bihercz, Gábor***; Beke, János; Kurják, Zoltán: Computer Aided Simulation of Thin Layer and Deep Bed Grain Drying Processes – Preliminary Resource

Results, In: *International Conference on Agricultural Engineering - 2002, Abstract, Part1,* pp. 183-184.

3.3. Beke, J.*; Kurják, Z.; **Bihercz, G.**: Microwave Field Test of Inner Moisture and Temperature Conditions of Beetroot, In: *IDS 2002, Beijing, China, Volume C., Series Editor: A. S. Mujumdar*, pp. 891-901.

3.4. **Bihercz, G.*,** Beke, J.; Kurják, Z.: Experimental analysis of drying process of carrot and tomato samples, In: *Proceedings of the 2nd Youth Symposium on Experimental Mechanics* (ISBN 88-901080-0-2-44406), Milano Marittima(Italy) – 2003; pp. 99-100

3.5. **Bihercz, G.*,** Kurják, Z.: Comparison of convective and microwave dying process of tomato and carrot samples, In: *Proceedings of the Symposium EUDrying '03*, 2003; pp. 268-277

3.6. **Bihercz, G.***, Kurják, Z.: A new designed convective model deep bed grain dryer for drying grained materials, In: *Proceedings of the 3rd Youth Symposium on Experimental Mechanics* (ISBN 88-901080-0-2-44406), Poretta Terme(Italy) – 2004; pp. 93-94

3.7. **Bihercz, G.***, Kurják, Z.: Comparative Analysis on Measured Data of some Vegetable Type under Microwave and Convective Treatments, In: *6th International Conference on Food Science – Summaries of Lectures and Posters*, Szeged, 2004, pp. 108-109

3.8. **Bihercz, G.***, Kurják, Z.: Analysis of the Microwave and Convective Vegetable Dewatering Process as a Function of Drying Conditions, In: *Drying 2004 – Proceedings of the 14th International Drying Symposium (IDS 2004),* Sao Paulo, Brazil, 22-25 August 2004, Vol. C. pp. 1652-1659

3.9. **Bihercz, G.*,** Kurják, Z.: Vegetable Drying Process as a Function of the Energy Transmission Method, *International Workshop and Symposium on Industrial Drying* - 2004, Mumbai, India, Ref. Number: HOME/PDF/SY123.pdf

3.10. **Bihercz, G.***, Kurják, Z.: Laboratory-scale Calibration of a Self-Made Model Deep Bed Grain Dryer for Corn Kernels, In: *Proceedings of the 4th Youth Symposium on Experimental Mechanics* (ISBN 88-901080-2-9-44406), Castrocaro Terme (Italy) – 2005; pp. 153-154

3.11. **Bihercz, G.***, Beke, J.: *Semi-Empirical Model of Convective Drying with Wide Range Layer Depth Validity*, Proceedings of the 11th Polish Drying Symposium (XI PDS), Poznan, Poland, 13-16 September 2005, HOME/Papers/Bihercz_Beke.pdf

Lectured Articles in Hungarian

4.1. **Bihercz, G.*,** Kurják, Z.: Sárgarépa- és paradicsomminták konvektív és mikrohullámú szárítási folyamatainak összehasonlítása, In: *Mezőgazdasági technika, 2003. augusztus*, pp. 2-5

4.2. **Bihercz, G.;** dr. Beke, J.: Kiterjesztett rétegvastagságú, félempirikus szárítási modell, In: *Mezőgazdasági technika, 2005. augusztus*, pp. 2-5

Research Reports, Essays

5.1. **Bihercz G**.*: Konvektív vastagrétegű terményszárító tervezése. Egyetemi TDK dolgozat SZIE Gépészmérnöki Kar Gödöllő, 2000. 79p.

5.2. **Bihercz G**.*: Konvektív vastagrétegű terményszárító tervezése. Országos TDK dolgozat NYME Sopron, 2001. 82p.

5.3. **Bihercz G**.*: Vastagrétegű, konvektív terményszárítási folyamat számítógépes szimulációja. Egyetemi diploma dolgozat SZIE Gépészmérnöki Kar Gödöllő, 2001. 81p.

International References

6.1. **Beke, J.**: Experimental Study of Dewatering Process on Vegetative Parts of some Agricultural Products, In: *Drying 2004 – Proceedings of the 14th International Drying Symposium (IDS 2004),* Sao Paulo, Brazil, 22-25 August 2004, Vol. C. pp. 1553-1560

6.2. **Molnár Ildikó, Dr. Szlivka Ferenc:** Operational Planning and Aerodynamically Calibration of a Convective Deep Bed Grain Model-Drier, In: *Proceedings of the 4th Youth Symposium on Experimental Mechanics* (ISBN 88-901080-2-9-44406), Castrocaro Terme (Italy) – 2005; pp. 59-60 (hivatkozás 3.4-re)

6.3. **Molnár Ildikó, Dr. Szlivka Ferenc:** Operational Planning and Aerodynamically Calibration of a Convective Deep Bed Grain Model-Drier, In: *Proceedings of the 4th Youth Symposium on Experimental Mechanics* (ISBN 88-901080-2-9-44406), Castrocaro Terme (Italy) – 2005; pp. 59-60 (hivatkozás 3.9-re)