Penerbit Akademia Baru

CFD Letters

Journal homepage: www.akademiabaru.com/cfdl.html
ISSN: 2180-1363

Apple convective drying - Part II: Scrutinization of monitoring parameters levels via Taguchi optimization approach

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ARTICLE INFO	ABSTRACT

Article history:
Received 15 December 2018
Received in revised form 15 February 2019
Accepted 28 February 2019
Available online 22 March 2019

Various parameters affecting the drying process of an apple were optimized by adopting the Taguchi experimental design technique (TEDT). Such a technique reduces the number of experiments while maintaining excellent accuracy and treating the measured values and their dispersion for the process parameters including the drying air temperature, the relative humidity, the velocity and the sample shape factor. The goal is to optimize the drying time as well as the internal mechanical stress as the average moisture content in the dried sample reaches value resultant in water activity of 90%. The optimized combination of conditions (parameters levels) were found to be in ranges: temperature [60, 70 °C], velocity [1.25, 2 m/s], relative humidity [5, 15%] and a sample shape ratio of 0.5 for an estimated average time $242.75\,min$ and an estimated mechanical stress $5.46e7\,MPa$. A confirmation test by COMSOL using the optimized conditions gives excellent agreement with the estimated values emerging from the TEDT optimization and resulting in around four hours of drying time.

Keywords:
Convective drying, apple processing, Taguchi experimental design, optimization, factors levels

1. Introduction

Drying is an important technique used for food preservation that not only consumes a considerable amount of energy but also effects product quality. In order to get an appropriate mathematical model and adequate parameters to describe this process, conducting an optimization of the drying conditions to minimize the drying time is essential so that, the energy consumed is preserved by adjusting the velocity, the temperature of the hot air flow. Also, the mechanical stresses are reduced in order to avoid fragmentation of the product, reaching the desired dehydration according to the dried product.

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The Taguchi experimental design is a distinguished technique of lower costs and high efficiency. This technique has generated a growing attention in engineering process [1-3]. The main idea of the TEDT is that it deals jointly with the average parameters that govern the system (product or process) and the dispersion (noise) to maintain a combination of stable and precise values of the operation parameters.

Many researchers well reported the optimization of a single performance characteristics or single response [4-9]. However, doing a multi-answer optimization is hard, more complicated and challenging because of its complexity. Indeed, the improvement of one answer can cause the degradation of other answers. A.H.A. Shah *et al.,* [10] conducted a multi-objective optimization by selecting two important parameters in CNC turning of S45 C Carbon steel using Taguchi and Grey Relational analysis method and experimental results proved that machining parameters can be enhanced by applying this approach. B. Satheesh Kumar *et al.,* [11] also conducted a multi response optimization for Turning AISI 1040 Steel with Extreme Pressure Additive included Vegetable Oil Based Cutting Fluids using Grey Relational Analysis.

It is proposed in this paper to conduct a two response optimization study of convective drying conditions for apple sample using the Taguchi experimental design. The later allows determining, in minimum of tests and with a maximum of precision, the influence of a certain number of parameters on the kinetics of drying and the mechanical behavior. Analysis and discussion of the results will be performed.

2. System Description

The objective of this study is to highlight the drying behavior according to the drying conditions. At first, a FE modeling and simulation has been carried out. The model consists of coupled heat conduction and mass diffusion equations along with the solid mechanics equations which are numerically implemented by means of COMSOL Multiphysics [12]. A symmetric geometry 2D of a 3D apple sample is considered in the simulation (Figure 1). The heat and mass transfer conditions are applied at all boundaries except at the limit of symmetry (y=0).

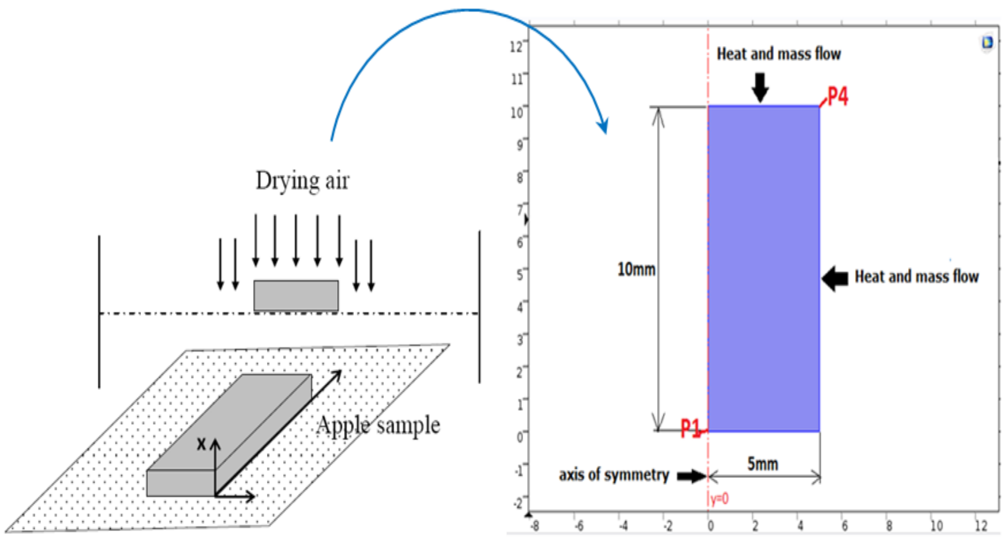

Fig. 1. Model configuration: a rectangular half plan is considered

3. Materials and Methods

The optimization of the drying conditions is conducted to minimise the drying time so preserve the energy consumed (by adjusting the velocity, the temperature of the hot air flow, etc.), minimizing the mechanical stresses to avoid fragmentation of the product, reaching the desired dehydration according to the dried product. The preservation of nutritional quality is also a decisive parameter in the quality of drying but not considered here. It is proposed in this part to conduct an optimization study of convective drying conditions for apple sample using the Taguchi experimental design. The later allows determining, in minimum of tests and with a maximum of precision, the influence of a certain number of parameters on the kinetics of drying and the mechanical behavior in order to optimize the performances of our study. Analysis and discussion of the results will be performed.

3.1. Preparation of the Experimental Plan

The main three steps defining an experimental plan are the objective of the study, the choice of the responses to reach the objective, and the choice of the factors and their levels as presented in the following:

3.1.1. Definition of the objective of the study

The objective of this study is to highlight the drying behavior according to the drying conditions. The study will focus on factors such as the maximum drying flow (residence time), time required to reach 90% dry matter, final volume and critical humidity, etc… and finally the optimization will be conducted.

3.1.2. Choosing the response to reach the goal

This study has two responses. The first will be the average drying time. The second response will be the limit constraint of Von Mises (mechanical stress) to avoid the problem of shrinkage and crusts at the surface of the apple.

3.1.3. Choice of factors, their levels and plans of experiences

Using fractional factorial experiment plan, three factors were chosen in our study at three levels: temperature, velocity, relative humidity of drying air, and shape ratio.

I. The drying air temperature varies between 40 and 70 °C.
II. The air velocity of the drying varies between 0.5 m / s and 2 m / s.
III. The relative humidity varies between 5% and 25%.
IV. The aspect ratio of the complete sample r = width / height = 0.5, 1 and 2.

Such levels are summarized in Table 1. The information given by each of the combinations of factor levels defines the fractional matrix that must be respected in order to properly perform the tests necessary to properly handle our optimization study. Indices 1 and 2 represent the minimum and maximum levels respectively.

Table 1
Parameters (factors) of the study and their levels

Factors	Level 1	Level 2
A	5%	25%
B	0.5 m/s	2 m/s
C	0.5	1
D	40°C	60°C

3.2. Realisation of Tests

In this experiment eight cases are performed. Each test depends on the levels of the factors being controlled and gives a result of a value y. This will allow to make an analysis of the mean value $\bar{y}$. However, taking the factor A_i at a level n_i results in certain variability in this level, that it is assumed to be Gaussian. This leads to do each test five times and this will allow a margin of confidence for each test represented through the calculated standard deviation. This will allow analyzing the variance of the results.

3.2.1. Mathematical tools

Before the tests are performed, a variation law for each controlled factor is defined because so that five tests for each treated case are performed in order to let extracting statistical values.

Simulation of a Gaussian distribution is performed using the Box-Muller method [13]. This technique, based on a transformation of Cartesian coordinates into polar coordinates, takes the uniform random variables (in]0, 1[) and independent U_1 and U_2 and produces standard independent random variables (μ = 0, σ = 1) X and Y (in] 0, 1 [). Reader may be referred to our previous studies for more details [14-16]. In our case, each parameter follows the normal law defined for example for the parameter A in its level 1 by:

$$A'1 = A1 + \sigma.X. \quad (1)$$

Where U1 and U2 are two random numbers

$$\theta = 2\pi\, U1 \quad (2)$$

$$R = \sqrt{-2\ln(U2)} \quad (3)$$

$$X = R\cos(\theta) \quad (4)$$

$$Y = R\sin(\theta) \quad (5)$$

A1 is the value of parameter A at level 1, σ represents 5% (or less) of the value of A1.

In reality, there is a dependence of temperature and relative humidity. Moisture has a remarkable influence on drying kinetics. This influence becomes more the weaker as the temperature increases. This is because the rate of evaporation is higher than the rate of diffusion of water inward to the surface of the sample thus forming a relatively impermeable surface crust.

Hence, there will be a slowing down of the drying process. The L8 experiment orthogonal array is adopted here (Table 2) to set the factors number and their levels as well as the number of interactions.

Table 2
L8 experiment orthogonal array (4 factors at 2 levels and 3 interactions)

N°case	Controlled factors				Interactions		
	A	B	C	D	AD	BD	CD
1	1	1	1	1	1	1	1
2	1	1	1	2	2	2	2
3	1	2	2	1	1	2	2
4	1	2	2	2	2	1	1
5	2	1	2	1	2	1	2
6	2	1	2	2	1	2	1
7	2	2	1	1	2	2	1
8	2	2	1	2	1	1	2

The values 1 and 2 correspond to upper and lower levels of the factors and in the interaction zone, they correspond to the various combinations (A1D1, A1D2, A2D1, ...).

3.2.2. Calculation of the signal/ noise ratio

The Signal / Noise ratio is an excellent performance indicator because it simultaneously takes into account the mean y of the measured values and the standard deviation of the measurements made. For this reason, the calculation of the latter was developed to determine the effect on the measurements made. The loss of quality function L is a statistical model for calculating the "cost" (the loss) of possible variations of certain parameters of the system. In our case, y is the answer, and s is the standard deviation or the dispersion of the measured values written as follows:

$$s^2 = \sigma_{n-1} = \sum(y_i - \bar{y})^2/(n-1) \tag{6}$$

$$S/B\ (dB) = -10\log_{10}(\mathrm{s}^2 + \bar{\mathrm{y}}^2) \tag{7}$$

Table 3 summarizes the calculation for the first response (time) and Table 4 summarizes the calculation for the second response (mechanical stress).

Table 3
Results of the simulations for the time response

Tests	Realizations (min)					Results		
N°	1	2	3	4	5	y_{moy}	S_{n-1}	S/B(dB)
1	398.9	430.9	419.0	394.9	421.4	413.0	15.4	-87.889
2	243.0	252.5	257.8	257.7	251.6	252.5	6.0	-83.611
3	791.7	804.2	772.0	851.7	769.6	797.8	33.3	-93.609
4	441.2	429.8	413.8	430.6	418.0	426.7	10.9	-88.167
5	797.7	848.3	775.3	866.8	733.0	804.2	54.3	-93.690
6	490.1	510.1	527.1	479.2	479.7	497.2	20.9	-89.502
7	444.1	404.7	428.8	419.3	366.4	412.7	29.6	-87.897
8	310.2	302.4	309.4	299.7	296.2	303.6	6.1	-85.210
Average of responses						488.5	_	-88.697

Table 4
Results of the simulations for the mechanical stress response $\boldsymbol{\sigma_{yy}}$

Tests	Realizations (MPa)					Results		
N°	1	2	3	4	5	y_{moy}	S_{n-1}	S/B(dB)
1	109.0	114.0	112.0	109.0	113.0	111.0	2.3	-161.0
2	48.3	49.9	50.9	51.4	49.8	50.1	1.2	-154.0
3	125.0	124.0	126.0	120.0	127.0	124.0	2.7	-162.0
4	70.1	70.7	70.7	70.5	70.2	70.4	0.3	-157.0
5	114.0	110.0	115.0	108.0	117.0	113.0	3.7	-161.0
6	42.9	43.3	42.5	45.6	44.6	43.8	1.3	-153.0
7	103.0	96.4	99.1	97.8	92.2	97.7	3.9	-160.0
8	31.8	33.6	31.3	31.0	35.1	32.6	1.7	-150.0
Average of responses						80.40	_	-157.0

3.2.3. Calculation of effects

The effect on the average value of a parameter X at its level j is written in its general form:

$$E_{X_j} = \frac{\sum_i K_{Xj}^i}{n} - K_{moy} \tag{8}$$

The results for the average drying time (min) and the mechanical stress value σ_{yy} (MPa) are shown in Tables 5 ad 6.

Table 5
Effect of parameters variation on the average drying time (min)

Average effect	Factor A	Factor B	Factor C	Factor D
Level 1	-16.0	3.3	-143.0	118.5
Level 2	16.0	-3.3	143.0	-118.5

Table 6
Effect of parameters variation on the average mechanical stress value σ_{yy} (MPa)

Average effect	Factor A	Factor B	Factor C	Factor D
Level 1	8.7	-0.9	-7.5	31.2
Level 2	-8.7	0.9	7.5	-31.2

The effect on the S / N ratio of a parameter X at its level j is written in its general form:

$$E_{X_j} = \frac{\sum_i S/N\left(X_j^i\right)}{n} - S/N_{avg} \tag{9}$$

Here X is the controlled parameter, $S/N\ (X_j^i)$ the effect value on S /N ratio of the factor X at its level j, corresponding to the test number i, n is the number i, $S/N\ avg$ is the average value of all S /N ratios. The effects on the S/N ratio are presented in Tables 7 and 8.

Table 7
Effects of parameters variation on S / N ratio (dB) (time)

Effect S/B	Factor A	Factor B	Factor C	Factor D
Level 1	0.378	0.024	2.545	-2.074
Level 2	-0.378	-0.024	-2.545	2.074

Table 8
Effects of parameters variation on S / N ratio (dB) (mechanical stress)

Effect S/B	Factor A	Factor B	Factor C	Factor D
Level 1	-1.229	0.014	0.967	-3.706
Level 2	1.229	-0.0142	-0.967	3.706

Besides, the interaction resulting from the combination of the levels of several factors is equal to the system response, minus the overall average, minus the sum of the effects of each of the factors, minus the sum of all the interactions of lower orders that may exist between these factors.

$$I_{A1B1C1} = \overline{A1B1C1} - \bar{T} - E_{A1} - E_{B1} - E_{C1} - I_{A1B1} - I_{A1C1} - I_{B1C1} \quad (10)$$

For instance, for the interaction AD, owing to know its value for each of the combinations: A1D1, A1D2, A2D1, A2D2. The value of the A1D1 interaction is given by the relation:

$$I_{A1D1} = \overline{A1D1} - \bar{T} - E_{A1} - E_{D1} \quad (11)$$

With E_{A1} and E_{D1} are the effects with respect to the general average $\bar{T}$, of the factors A et D at level 1; ($\overline{\mathrm{A1D1}}$) average of test results where the AD interaction is at level 1; ($\overline{\mathrm{A1B1C1}}$) average of test results where the ABC interaction is at level 1. The results of interaction calculations are presented Table 9.

4. Results and Discussion

4.1. Effects Analysis

The goal is to determine the combination of factor levels that minimizes drying time and the mechanical stress σ_{yy} by ensuring good certainty. In fact, minimizing the drying time allows to gain energy and minimize the mechanical stresses allows sinking the fractionation and cracking of the apple sample, which makes it possible to market them in the intact and compact forms.

Table 9
Calculation of interactions

Interactions	Time		Stress	
	Average value	10^{-6} S/N(dB)	Average value	S/N (dB)
A1D1	867.125	-2.36	-0.356	0.734
A1D2	-867.125	2.36	0.356	-0.734
A2D1	-867.125	2.36	0.356	-0.734
A2D2	867.125	-2.36	-0.356	0.734
B1D1	-95.625	1.41	-0.042	-0.086
B1D2	95.625	-1.41	0.042	0.086
B2D1	95.625	-1.41	0.042	0.086
B2D2	-95.625	1.41	-0.042	-0.086
C1D1	-3063.875	0.438	0.333	-0.415

C1D2	3063.875	-0.438	-0.333	0.415
C2D1	3063.875	-0.438	-0.333	0.415
C2D2	-3063.875	0.438	0.333	-0.415

In this part, the graphs of the effects of the parameters A, B, C and D on the average value and the dispersion (variability) will be analyzed through Figures 2, 3, 4 and 5. Such figures are obtained using values in Tables 5, 6, 7 and 8. Parameters are taken in their levels which do not influence the average values and at the same time which makes maximize the ratio S/N (dB). This is for the purpose of keeping a value of K more or less close to the average value of the tests and to guarantee a low dispersion around this value. It is now interesting to compare, with the help of graphs, the two types of results concerning:

I. The average value of the drying time and the corresponding mechanical stress.
II. The S / N ratio (dB) for both responses.

It is essential to know that the higher the algebraic value of S/N (dB), the lower is the generated loss so the better the performance of the drying process. The Signal / Noise ratio should therefore be used first to make the right choice of factor levels.

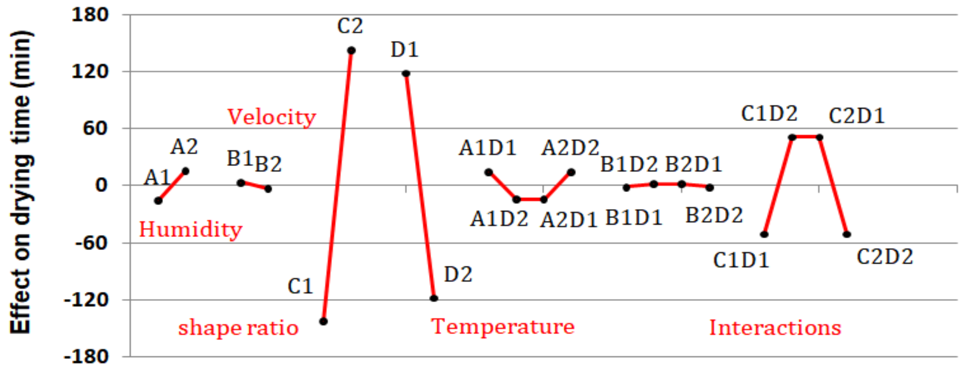

Fig. 2. Effect of parameters levels variation on average drying time

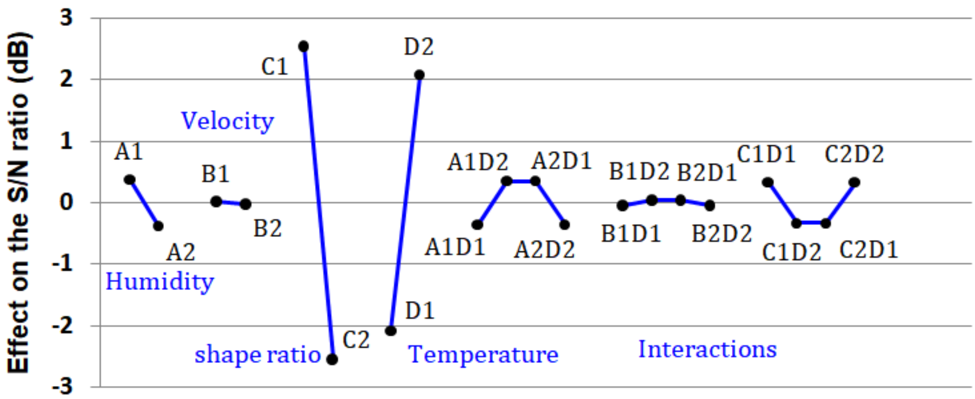

Fig. 3. Effect of parameters levels variation on the Signal/Noise ratio (drying time)

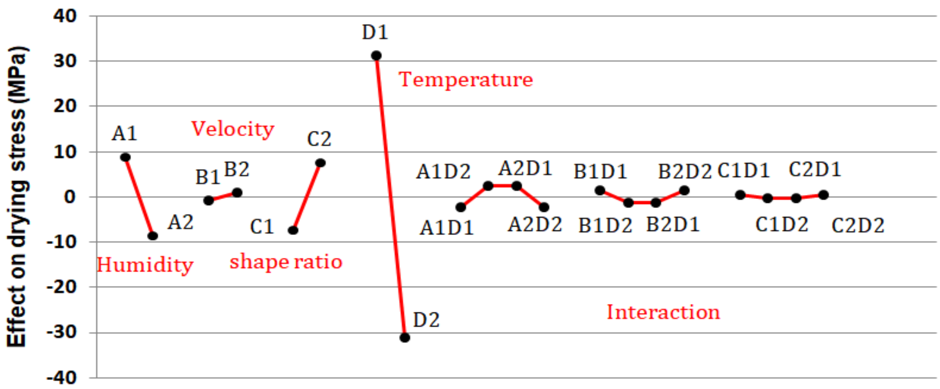

Fig. 4. Effect of parameters levels variation on the average value of mechanical stress

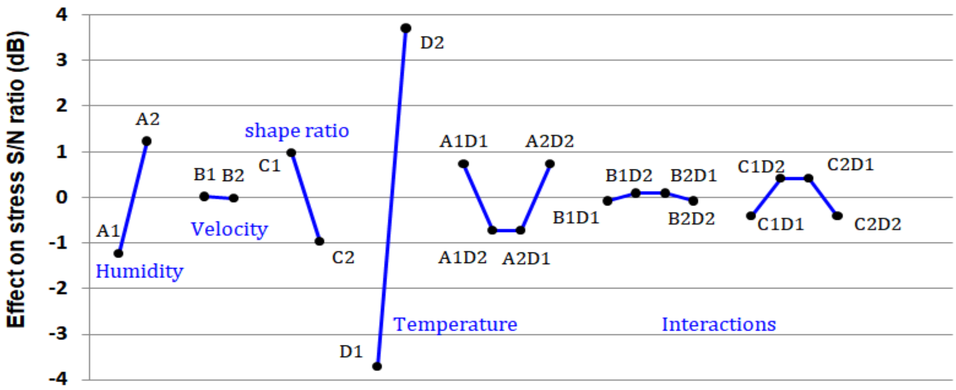

Fig. 5. Effect of parameters levels variation on the signal/noise ratio (mechanical stress)

For the relative humidity factor (A), level 1 seems to be the best for time distribution since it minimizes the average value of drying time and increases the S / N ratio. However, the level 1 has an opposite effect on the mechanical stress but, it is advantageous to minimize the time than the mechanical stress. In addition, the level 1 of the relative humidity is in important relation with the level 2 of the temperature. The interaction between level 1 of factor A and level 2 of factor D is favored because it decreases the mean value of time. Therefore, the choice is made on the levels A1 and D2 and the I_{A1D2} interaction.

For the velocity (B), it is noticed a slightly negligible effect on the kinetics of drying. This is explained by the low value of the external resistance to the transfer of moisture relative to that of the internal resistance. The interaction between factor B and D has no great effect on drying kinetics as well as mechanical stress. Choosing level 2 of the factor B will minimize the average value of time and has no effect on the mechanical stress and the interaction I_{B2D2}. The aspect ratio has a significant Effect on the drying kinetics. Indeed, the drying time of an apple sample of initial thickness 10 mm is almost equal to twice the drying time relative to a thinner sample of thickness 5 mm. it is advantageous to choose level 1 of the form ratio (C) for the same reasons. The choice is also made on the interaction I_{C1D2}.

Factor D (temperature) is very influential on the drying process. Indeed, it is a factor of first order and induces a major difference on the average value. Indeed, the increase of the temperature causes an increase of the water diffusivity and consequently an acceleration of the internal migration of the water. Thus, the drying time is shorter than the temperature is high, which is explained by the increase of the exchange potential between the air and the product thus promoting the evaporation of water. To reduce the dispersion of the results, it is advantageous to choose the level 2 of the factor B. It contributes at the same time to minimizing the average drying time and the mechanical stress.

4.2. Retained Combination and Synthesis

The final combination is: $A_1.B_2.C_1.D_2$. The resulting effect is given by the equation below:

$$E_{rés} = E_{A_1} + E_{B_2} + E_{C_1} + E_{D_2} \tag{12}$$

Means that $HR = 5\%;\ V = 2\ ms^{-1}; D = 0.5\ and\ \ T = 70°C$.
The results of the experimental plans are:

$$\hat{y} = \ \overline{K} + E_{rés} + I\ et\ \ \widehat{S/B} = \overline{S/B} + E_{rés} + I \tag{13}$$

For the drying time:

$$\hat{y} = 29307.375 + (-957.375 - 196.875 - 8580.875 - 7108.375) + (-867.125 - 95.625 + 3063.875) = 14565s \tag{14}$$

$$\widehat{S/B} = -88.697 + (0.378 - 0.0240 + 2.545 + 2.074) + (0.355 + 0.042) = -83.660\ dB \tag{15}$$

For the mechanical stress:

$$\hat{y} = 8.04e^7 + (8.68e^6 + 8.83e^5 - 7.46e^6 - 3.12e^7) + (2.36e^6 + 1.41e^6 - 4.38e^5) = 5.46e^7 \tag{16}$$

$$\widehat{S/B} = -157 + (-1.23 - 0.0142 + 0.967 + 3.71) + (-0.734 - 0.086 + 0.415) = -154dB \tag{17}$$

4.3. Confirmation Test

The configuration and retained factors levels of the optimization study are injected in a COMSOL simulation. Acceptable results were obtained. For a drying of 90%, one may find a time

$$t = 15345\ s = 255.75\ min \tag{18}$$

and a mechanical stress of value

$$\sigma_{yy} = 5.09e7MPa \tag{19}$$

which are close to the estimated average time and mechanical stress values

$$t = 14565\ s = 242.75\ \text{min}\ and\ \sigma_{yy} = 5.46e7\ MPa \tag{20}$$

which corresponds to a drying of 88.67% (see Figures 6 and 7).

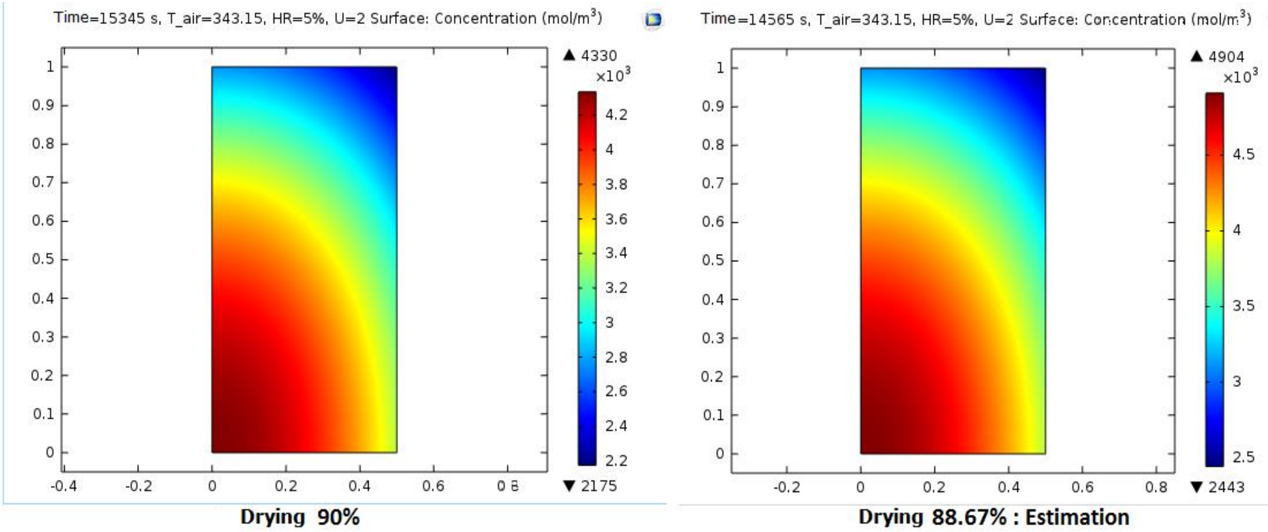

Fig. 6. Comparison concentration contours (mol/m^3) for model values (left) and estimation (right)

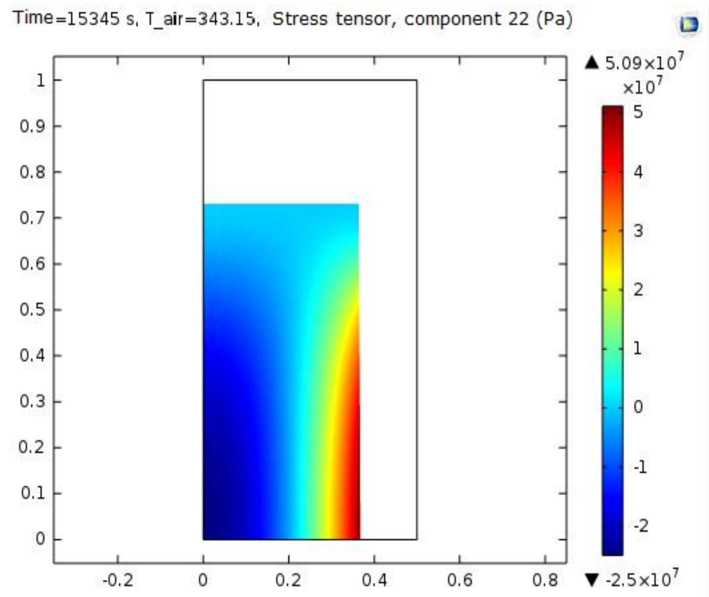

Fig. 7. Distribution of mechanical stress component $\boldsymbol{\sigma_{yy}}$

The results obtained here-above are in a good accordance with the results estimated by the Taguchi experimental design as a mean value rather than a dispersion of the results. It has been possible to minimize the average drying time and the average mechanical stress as well. The analysis of the effects on the measured value and the S / N ratio gives an optimal combination of the most influential effects to minimize the measured value (y) by guaranteeing a robustness of the expected result. It can be noted that increasing the temperature and velocity and decreasing the relative humidity of the drying air significantly reduces the drying time. In addition, the drying time decreases with the decrease of the initial thickness of the sample.

5. Conclusion

An optimization study on the drying conditions (parameters ranging in usual levels) was conducted by the help of the TEDT. The goal is to optimize the drying time to a set rate of moisture content and minimize the residual mechanical stresses. The two response parameters are considered as the measured or mean value $\overline{y}$. A fractional experimentation plan of 8×5 trials (5 factors, 2 levels and 3 interactions) was considered, taking into account linear effects and some possible factors interactions. The analysis of the effects on the measured values and the S/N ratio leads to a mathematical model (combination of factor levels) that reduces the average value of drying time and average mechanical stress while minimizing dispersion. This effects study gave an optimal combination of the most influential effects to minimize the measured value $\bar{y}$ by ensuring robustness of the expected result.

A confirmatory test of retained optimized parameters levels was then maintained and aimed at confirming that the factors combination adopted following the experimental design study allows the expected profitability of the model. Indeed, it has been noticed following this test that the increase of the temperature and the velocity and the decrease of the relative humidity of the drying air, as well as the reduction of the shape ratio significantly reduces the drying time and the mechanical stress. The present study allowed giving a better quantitative insight, given the specific drying conditions and reducing energy consumption and time treatment.

The model developed can be a predictive tool for the local analysis of the behavior of the product during drying and in particular, any undesirable constraints and deformations for the quality of the finished product. The results obtained can be in perspective of an experimental confirmation.

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