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To cite this article: Alijon Kholikov *et al* 2021 *IOP Conf. Ser.: Earth Environ. Sci.* **848** 012010

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Optimization of onion drying process parameters using the full factorial experiment method

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Abstract. Evaluation of the effectiveness of the influence of the main factors on drying using heat pipes, such as temperature, drying time and layer thickness of onions, was carried out for the first time using the method of full factorial experiment. For this, the variables were encoded, the experiment planning matrix was compiled, the regression equations were calculated, the equation was checked for adequacy, and a posteriori analysis was performed. The main factors influencing the drying of sliced onions in drying installations using heat pipes have been determined. The optimal mode of onion drying in a drying plant using heat pipes has been determined.

1. Introduction

Drying is a complex non-stationary process of liquid removal by evaporation, i.e. heat and mass transfer. The importance of drying lies in the fact that the dried product retains its original nutritional properties and becomes more durable during storage. [1; 2; 3;].

Studies of the preservation of vitamins and other useful substances in vegetables, fruits and berries with various processing technologies show that the greatest safety is provided by drying fruits, which can most of all be stored for a long time without spoiling it. Therefore, the study of such processes is increasingly attracting researchers at the present time.

In [4], a solar powered forced convection dehumidifier was developed to study the effects of air flow rate (2.43, 5.25, 8.09 kg/min), air temperature (55, 65, 75°C) and proportion of recirculated air (up to 90%) on the total energy requirement for drying onion slices. The dryer was equipped with a flat plate solar air heater having both corrugations and triangular ribs on the absorber plate. To dry the onion slices from an initial moisture content of about 86% (wet basis) to a final moisture content of about 7% (wet basis), the energy required per unit mass of water removed without using air recirculation was 23.548 to 62.117 MJ/kg water. The share of solar air heater, electric heater and blower ranges from 24.5% to 44.5%, 40.2% and 66.9% and 8.6% and 16.3%, respectively. Total energy savings due to the proportion of recirculated air were determined at air temperatures of 65 and 75 °C for the above three air flow rates. Maximum energy savings of up to 70.7% have been achieved by recirculating exhaust air. The energy required per unit mass of removed water is from 12.040 to 38.777 MJ/ kg of water. The share of solar heater, auxiliary heater and blower energy ranges from 22.4% to 40.9%, 33.6% and 62.6%, as well as 11.2% and 37.2%, respectively.

The aim [5] of the work of the study was to develop a dryer for direct solar cells with a photovoltaic module and to evaluate its efficiency in experiments with natural and forced convection. The



photovoltaic module supplies power to eight coolers, which allow the air inside the equipment to be refreshed. In this configuration, the dryer is able to operate independently of the power distribution network. When drying green onions, humidity and colorimetric parameters were monitored. Drying kinetics showed a period of constant speed followed by a period of decline for both operating conditions. The convection experiment showed a higher speed, and external mechanisms could control the process. Straight lines have been adjusted for constant rate periods from $R^2=0.999$. The effective diffusion coefficient values were $5.15 \times 10^{-9} \text{ m}^2/\text{s}$ and $1.15 \times 10^{-8} \text{ m}^2/\text{s}$ for natural and forced convection drying. The average solar dryer efficiency and specific energy consumption were 34.2%, 18.3 kWh/kg for the natural convection drying process and 38.3%, 16.4 kWh/kg for the forced convection drying process. Slight color changes were observed between fresh and dried green onions under two operating conditions, consistent with the need to maintain the green color of the material.

Among vegetables, drying of onions is also of the greatest importance, which plays a large role in people's lives. Dried onions are a natural product that can become an alternative to any seasoning and are one of the main industrial crops. The demand for dried onions is increasing every year. Currently, the production of dried onions is starting to develop. At the same time, they try to look for economical energy-saving technologies that are presented in the works [6; 7; 8;]. One of these is technologies based on renewable energy sources, which include the so-called heat pipes. [9; 10; 11;]

A heat pipe is a heat transfer device capable of transmitting large heat powers at low temperature gradients. A heat pipe (HP) is a sealed structure (a pipe made of a heat-conducting metal), partially filled with a heat-transfer fluid (a volatile liquid). In the heated part of the HP (in the heating or evaporation zone), the liquid heat carrier evaporates with heat absorption, and in the cooled part of the HP (in the cooling or condensation zone), the vapor flowing from the evaporation zone condenses with the release of heat. The movement of steam from the evaporation zone to the condensation zone occurs due to the difference in saturated steam pressure, determined by the temperature difference in the evaporation and condensation zones. The return of the liquid to the evaporation zone is carried out either due to external influences (for example, gravity), or under the action of a capillary pressure difference along the capillary structure (wick) located inside the HP (most often on its walls). Due to the fact that HPs with a capillary structure for liquid return can work regardless of orientation in the gravity field and in zero gravity. [9; 10;]

The capillary effect used in modern heat pipes is due to the ability of condensed liquid to move through thin capillaries (pores) in any direction. This effect is observed if you put a sponge in a puddle of water. The cavity of the copper tube is filled with various materials, wicks, porous ceramics, etc. [9; 10; 12; 13; 14]

Materials and refrigerants for heat pipes are selected based on the application, from liquid helium for ultra low temperatures to mercury for high temperature applications. However, most modern tubing uses ammonia or water as the working fluid. Low weight, high reliability and autonomy of TT operation, high effective thermal conductivity, and the possibility of using it as a thermostatic device led to the use of TT in power engineering, chemical technology, space technology, electronics and a number of other areas of technology. [9; 10;]

The use of HP for the preparation of a heating working agent instead of traditional installations, where it is heated by mixing with the combustion products of diesel fuel in special chambers, can significantly improve the quality of the finished product and eliminate air pollution. In addition, the heat pipe makes it possible to carry out heating and cooling of various technological streams in the same heat and mass transfer unit, which is especially important for modern farms that consume a large amount of heat and cold when processing raw materials. For the widespread introduction of these installations, it is necessary to substantiate the feasibility of their use and develop scientifically grounded rational temperature modes of operation of energy-saving installations during the processing of certain food and agricultural products, methods for calculating and designing installations.

The use of heat pipes powered by solar energy will increase the energy efficiency of heat and mass transfer installations. Among the many exceptional advantages of using a heat pipe as a heat transfer device, one can single out: simplicity of design, exceptional maneuverability in operation, ease of

regulation and the ability to transfer high heat fluxes over a considerable distance at extremely low temperature differences. Moreover, heat pipes do not require energy to pump the heat carrier. [9; 10; 15; 16; 17; 18; 19; 20]

In this regard, for the implementation of the task, one of the main directions is the development of mathematical models and the study of the influence of factors, the choice of optimal working agents and the design of heat pipes for specific heat and mass transfer installations. [21; 22; 23]

Carrying out experiments on drying vegetables and fruits using heat pipes and finding regression equations based on them allows you to find parameters that optimize the behavior of the system.

2. The purpose of the study

The purpose of this study is mathematical modeling of the drying process of sliced onions, the experiments of which were carried out by us using heat pipes. At the same time, the method of a full factorial experiment was chosen for the modeling apparatus, which allows you to select the main optimization parameters and influencing factors, the choice of the main level and the variation interval for each factor, check the reproducibility of the experimental results, build a mathematical model with the calculation of the coefficients of the regression equation, check the adequacy of the regression equation, interpretation of the regression equation.

3. Methods and materials

As a rule, modeling is carried out to find the optimal parameters of the system. At the same time, after some experimental studies, regression equations are obtained on their basis. If the factors influencing the investigated value lie in the interval between some upper and lower levels, a full factorial experiment is applied (FFE) [24; 25; 26; 27].

The purpose of experiment planning is to find such conditions and rules for performing research under which it is possible to obtain reliable and reliable information about an object with minimal labor input, and, in addition, to show this information in a compact and favorable form with a quantitative assessment of accuracy.

In our study, chopped onions with a moisture content of 89% were selected for drying, and practice shows that after drying at 12% moisture content, onions are considered optimal.

During the experiments, the following main factors influencing the process were established: drying temperature, drying time, thickness of sliced onions. And also determined the main intervals of variation of these factors.

The planning of a factorial experiment is based on the implementation of all possible combinations and investigated factors at three levels, that is, to implement these plans, 2^3 experiments should be put.

Then, based on the results of a full factorial experiment, it is necessary to determine 8 regression coefficients in the equation

$$y = b_0 + b_1x_1 + b_2x_2 + b_3x_3 + b_{12}x_1x_2 + b_{13}x_1x_3 + b_{23}x_2x_3 + b_{123}x_1x_2x_3 \quad (1)$$

Within the framework of the FFE, for processing the results of the given results and further determining the coefficients of the regression equation, the factors lead to the same scale. This is accomplished by encoding the variables.

Following the PFE theory, we will perform the following: denote the main factors and their intervals of variation:

Z_1 – drying temperature ($^{\circ}\text{C}$), $Z_1^- = 55$, $Z_1^+ = 65$;

Z_2 – onion drying time (min), $Z_2^- = 240$, $Z_2^+ = 420$;

Z_3 – layer thickness of sliced onions (mm), $Z_3^- = 3$, $Z_3^+ = 5$.

It is required to construct a regression equation, taking into account all interactions of factors, to check the obtained model for adequacy and to make its interpretation. The initial planning matrix for FFE 2^3 is shown in table 1.

Table 1. FFE planning matrix 2^3 .

No. experiment	Studied factors			Experimental results		
	z_1	z_2	z_3	y_1	y_2	y_3
1	–	–	–	16.3	17.7	16.5
2	–	+	–	6.6	7.4	8.3
3	+	–	–	8.8	9.2	8.5
4	+	+	–	5.1	5.4	5.7
5	–	–	+	35.1	34.4	35.2
6	–	+	+	18.5	17.4	17.7
7	+	–	+	24.1	24.8	25.6
8	+	+	+	11.8	12.2	12.5

We carry out the work in the following order:

1. we encode the variables;
2. we complete the planning matrix in coded variables, taking into account paired interactions and supplement with a column of average response values;
3. calculate the coefficients of the regression equation;
4. we check the calculated coefficients for significance, having previously determined the reproducibility variance, and we obtain the regression equation in coded variables;
5. check the resulting equation for adequacy;
6. we carry out the interpretation of the resulting model;
7. write out the regression equation in natural variables.

1. For each factor, we find the center, the variation interval and the dependence of the coded variable x_i on the natural z_i .

Based on the equations of the influencing factors on the moisture content of the onion, which were obtained during the experiments, we draw up the following factor coding table. We present the results in table 2.

Table 2. Coding factors.

Factors	Upper level $+i$	Lower level $-i$	Centre Z_i^0	Variation interval λ_i	Dependence of the encoded variable on the natural
z_1	65	55	60	5	$X_1 = \frac{Z_1 - 60}{5};$
z_2	420	240	330	90	$X_2 = \frac{Z_2 - 330}{90};$
z_3	5	3	4	1	$X_3 = Z_3 - 4;$

2. We calculate the average sample results for each experiment:

$$\bar{y}_i = \frac{(y_{1i} + y_{2i} + y_{3i})}{3} \quad (2)$$

where i- the number of the experiment.

We build a planning matrix taking into account all interactions and average response values in coded units. Here we present auxiliary graphs necessary for calculating the regression coefficients b_{ij} and b_{ijk} . The planning matrix for processing the results is shown in table 3.

Table 3. Scheduling matrix taking into account all interactions and average response values in coded units.

No. experimen t	Factors			Interactions				Experimental results			Average results
	x_1	x_2	x_3	x_1x_2	x_1x_3	x_2x_3	$x_1x_2x_3$	y_1	y_2	y_3	\bar{y}_j
1	-1	-1	-1	1	1	1	-1	16.3	17.7	16.5	16.833
2	-1	1	-1	-1	1	-1	1	6.6	7.4	8.3	7.433
3	1	-1	-1	-1	-1	1	1	8.8	9.2	8.5	8.833
4	1	1	-1	1	-1	-1	-1	5.1	5.4	5.7	5.400
5	-1	-1	1	1	-1	-1	1	35.1	34.4	35.2	34.900
6	-1	1	1	-1	-1	1	-1	18.5	17.4	17.7	17.867
7	1	-1	1	-1	1	-1	-1	24.1	24.8	25.6	24.833
8	1	1	1	1	1	1	1	11.8	12.2	12.5	12.167

3. The coefficients of the regression equation are determined by the following formulas.

$$b_0 = \frac{1}{n} \sum_{j=1}^n \bar{y}_j \quad (3)$$

$$b_i = \frac{1}{n} \sum_{j=1}^n x_{ji} \bar{y}_j, \quad i=1, \bar{k} \quad (4)$$

$$b_i = \frac{1}{n} \sum_{j=1}^n x_{jr} x_{ip} \bar{y}_j, \quad r < P, r = \bar{i}, \bar{k}, \quad P = \bar{1}, \bar{k} \quad (5)$$

$$b_{1,2,3} = \frac{1}{n} \sum_{j=1}^n x_{j1} x_{j2} x_{j3} \bar{y}_j \quad (6)$$

Using the values of table 3 and the formula, we find the coefficients of the regression equation (1), where it is shown in table 4.

Table 4. Regression equation coefficients.

b_0	b_1	b_2	b_3	$b_{1,2}$	$b_{1,3}$	$b_{2,3}$	$b_{1,2,3}$
16.0333	-3.2250	-5.3167	6.4083	1.2917	-0.7167	-2.1083	-0.2000

4. Some of the coefficients in the regression equation written on the basis of table 4. may turn out to be negligible and insignificant. To establish whether the coefficient is significant or not, let's do the following:

calculate the reproducibility estimate $S_{\{y\}}^2$.

$$S_{\{y\}}^2 = \frac{1}{n(m-1)} \sum_{j=1}^n \sum_{i=1}^m (y_{ji} - \bar{y}_j)^2 = \frac{1}{n} \sum_{j=1}^n \left(\frac{1}{m-1} \sum_{i=1}^m (y_{ji} - \bar{y}_j)^2 \right) = \frac{1}{n} \sum_{j=1}^n S_j^2 \quad (7)$$

Where n- the number of experiments (the number of rows in the matrix of the FFE);

m- the number of experiments in each experiment;

y_{ji} - the result of a separate i-th observation in the j-th experiment.

\bar{y}_j - sample values of observations for the j-th experiment.

For convenience, we draw up the calculations in the form of table 5.

Table 5. Calculations for variance reproducibility.

j	y_1	y_2	y_3	\bar{y}_j	$(y_{j1} - \bar{y}_j)^2$	$(y_{j2} - \bar{y}_j)^2$	$(y_{j3} - \bar{y}_j)^2$	S_j^2
1	16.3	17.7	16.5	16.833	0.2844	0.7511	0.1111	0.5733
2	6.6	7.4	8.3	7.433	0.6944	0.0011	0.7511	0.7233
3	8.8	9.2	8.5	8.833	0.0011	0.1344	0.1111	0.1233
4	5.1	5.4	5.7	5.400	0.0900	0.0000	0.0900	0.0900
5	35.1	34.4	35.2	34.900	0.0400	0.2500	0.0900	0.1900
6	18.5	17.4	17.7	17.867	0.4011	0.2178	0.0278	0.3233
7	24.1	24.8	25.6	24.833	0.5378	0.0011	0.5878	0.5633
8	11.8	12.2	12.5	12.167	0.1344	0.0011	0.1111	0.1233

Summing up the elements of the last column of table 5, we get:

$$\sum_{j=1}^n S_j^2 = 2.71$$

From formula (7) we obtain the reproducibility variance:

$$S_{\{y\}}^2 = \frac{1}{8} \sum_{j=1}^8 S_j^2 = \frac{1}{8} \cdot 2.71 = 0.3388$$

Determine the standard deviation of the coefficients:

$$S_{coef} = \sqrt{\frac{S_{\{y\}}^2}{n \cdot m}} = \sqrt{\frac{0.3388}{8 \cdot 3}} = 0.1188 \quad (8)$$

From the tables of the Student's distribution by the number of degrees of freedom $n(m-1)=8 \cdot 2=16$ at significance level $\alpha = 0.05$ find $t_{cr.} = 2.12$. Consequently, $t_{cr.} \cdot S_{coef} = 2.12 \cdot 0.1188 = 0.25185 \approx 0.252$.

Comparing the obtained value of $t_{cr.} \cdot S_{coef} \approx 0$, with the coefficients of the regression equation presented in table 4, we see that all except $b_{1,2,3}$ coefficients are larger in absolute value 0.252. Therefore, except for $b_{1,2,3}$ all coefficients are significant. Assuming $b_{1,2,3} = 0$, we obtain the regression equation in coded variables:

$$y = 16.03 - 3.23x_1 - 5.32x_2 + 6.41x_3 + 1.29x_1x_2 - 0.72x_1x_3 - 2.11x_2x_3 \quad (9)$$

5. Let us check the obtained equation (9) for adequacy according to the Fisher criterion. Since the reproducibility variance was found in the previous paragraph, to determine the calculated value of the F_{calc} criterion, it is necessary to calculate the residual variance S^2_{res} .

To do this, we find the values of the studied parameter according to the obtained regression equation \tilde{y}_j ($j = 1, \dots, 8$), substituting +1 or -1 instead of x_i in accordance with the number j of the experiment from table 4:

The residual variance S^2_{res} is calculated by the formula (10):

$$S^2_{res} = \frac{3}{8-7} \sum_{j=1}^8 (\tilde{y}_j - \bar{y}_j)^2 = 0.96 \quad (10)$$

The calculated value of the Fisher criterion F_{calc} is determined by the formula (11):

$$F_{calc} = \frac{S^2_{res}}{S^2_{\{y\}}} = \frac{0.96}{0.3388} = 2.83 \quad (11)$$

Table value of the criterion F_{tabu} we find from tables the critical points of the Fisher distribution at a significance level $\alpha=0,05$ for the corresponding degrees of freedom $k_1=n-r=8-7=1$ and $k_2=n(m-1) = 8 \cdot 2 = 16$:

$$F_{tabu} = 4.49$$

Since $F_{calc}=2.83 < F_{abu} = 4.49$, the regression equation (9) is adequate.

4. Results and discussion

Let us interpret the resulting model (9). The equation shows that the strongest influence is exerted by the factor x_3 , x_2 and x_1 the thickness of the onion layer, the drying time and the drying temperature, since they have the largest coefficient in absolute value. After him, in terms of the strength of influence on the response, there are: double interaction factors x_2x_3 (drying time and layer thickness of onions) and x_1x_2 (drying temperature and drying time) then double interaction factors x_1x_3 (drying temperature and onion layer thickness).

We write out the regression equation (9) in natural variables, substituting instead of x_i their expressions through z_i , which we take from the last column of table 2.

$$y = 16.03 - 3.23\left(\frac{Z_1 - 60}{5}\right) - 5.32\left(\frac{Z_2 - 330}{90}\right) + 6.41(Z_3 - 4) + 1.29\left(\frac{Z_1 - 60}{5}\right)\left(\frac{Z_2 - 330}{90}\right) - 0.72\left(\frac{Z_1 - 60}{5}\right)(Z_3 - 4) - 2.11\left(\frac{Z_2 - 330}{90}\right)(Z_3 - 4) \quad (12)$$

Transforming this equation, we finally get its form in natural variables:

$$y = 39.9 - 1.016z_1 - 0.1374z_2 + 22.79x_3 + 0.0029z_1z_2 - 0.144z_1z_3 - 0.0234z_2z_3 \quad (13)$$

As you can see the interpretation of the regression equation in natural variables is identical to the equation in the coded variables.

To solve optimal optimization problems, they mainly use methods for studying the function of classical analysis, methods based on the use of indefinite Lagrange multipliers, as well as calculus of variations, dynamic programming, linear and nonlinear programming, etc.

As a rule, it is impossible to recommend any one method for solving all problems arising in practice

without exception.

The best way to select the optimization method that is most suitable for solving the corresponding problem is to explore the possibilities of applying various optimization methods.

Nonlinear programming methods are used to solve optimal problems with nonlinear target functions. The method of nonlinear programming combines a large group of numerical methods, many of which are adapted for solving optimal problems of the corresponding class. A number of nonlinear programming methods are almost constantly used in combination with other optimization methods (for example, the scan method in dynamic programming).

The scanning method consists in sequentially scanning the optimality criterion at a number of points belonging to the region of variation of the independent variables and finding among these points one in which the optimality criterion has the maximum (minimum) value. The accuracy of the method, of course, is determined by the fact that the selected points are so "densely" located in the permissible range of variation of the independent variables.

The main advantage of the scanning method is that the use of sufficiently "densely" located points of interest always guarantees finding the global optimum, since the entire range of variation of independent variables is analyzed.

In this regard, to solve the problem of optimizing the drying process of onions using heat pipes, we have chosen the scanning method.

We select the criteria for the optimality of the onion drying process using heat pipes, the final moisture content of the onion.

$$Y_{\text{out}} = f(t, \tau, \delta) \rightarrow Y_{\text{out}} \rightarrow \min \quad (14)$$

When searching with the scanning method, we find the smallest coordinates that the minimum moisture output is found:

For temperatures from 55°C to 65°C, for a time from 240 minutes to 420 minutes, for onion layer thickness from 3 mm to 5 mm, and product yield (humidity) from 5.4% to 34.9%. These findings can be confirmed using three-dimensional graphs.

The properties of the obtained regression equation can be seen in the following graphs. To do this, we fix one of the three factors, then we can get a three-dimensional graph.

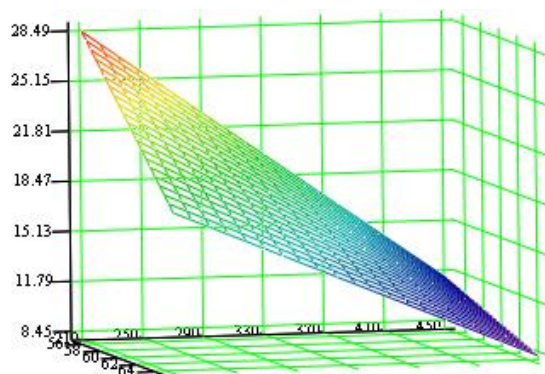


Figure 1. Influence of temperature and drying time to product moisture at a fixed onion layer thickness of 4 mm.

In figure 1, the effect of temperature and drying time on the moisture content of the product is shown at a fixed value of the onion layer thickness equal to 4 mm. The figure shows that with an increase in temperature and drying time, the moisture content of the product decreases. The minimum humidity is obtained at the maximum values of temperature and drying time. The maximum humidity is obtained with the minimum values of temperature and drying time. For a long time and at a minimum temperature value, a decrease in product moisture is also observed, but not at the same level as at the maximum temperature and time values.

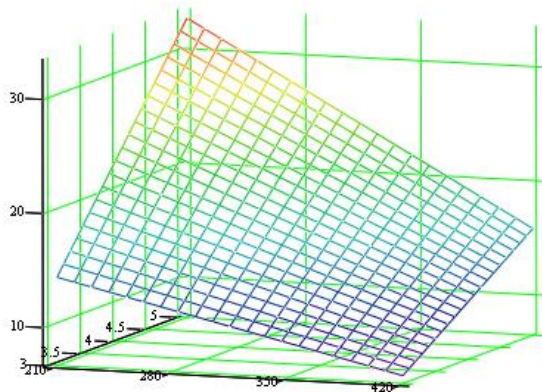


Figure 2. Influence of onion layer thickness and drying time to product moisture at a fixed temperature.

Figure 2 shows the effect of onion layer thickness and drying time on the moisture content of the product at a fixed temperature value of 60 degrees. It can be seen from the graph that with a decrease in the thickness of the onion layer and with an increase in the drying time, the moisture content of the product is killed and takes on a minimum value at a minimum thickness value and a maximum time value. Likewise, the maximum moisture value is obtained at the initial stage of the drying time and the maximum value for the thickness of the onion slices. These conclusions drawn from the graphs are consistent with the physics of the process.

5. Conclusion

After the statistical analysis and description of the regression equation graph, it can be concluded that the obtained mathematical model adequately describes the drying process of onions.

With the criterion of the optimality of the drying process of onions using heat pipes and from three-dimensional graphs, it can be concluded at a temperature of 60°C, the thickness of the onion layer is 4 mm, the drying time is 300 minutes at an air speed of 3 m/s, the optimal drying mode, which onion moisture reaches up to 12 %.

Thus, the use of a full factorial experiment to simulate the drying of products makes it possible to determine the degree of influence of factors on the output parameters of the system. The use of this approach in the development of drying plants makes it possible to develop flexible management strategies and a comprehensive assessment of situations that are implemented in the agricultural sector.

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