UPDATE OF THE PROCEDURE USED FOR HEAVY CLAY DRYER OPTIMIZATION

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The description of the moisture transfer in porous media during drying was the subject of many scientific studies. The unique drying theory was developed five years ago and has recently won a general recognition in the scientific community. This paper is providing the update of the recently reported method for setting up the optimal drying parameters inside the heavy clay dryer. The main goal of this paper was to find a way how to reduce the number of experiments without affecting the quality of the previously proposed calculation method. The critical drying rate, as well as the drying behavior can be easily registered inside the laboratory recirculation dryer for any heavy clay product. These data provides a clear perception of how far the real drying curve, used in industrial dryer, is away from the shortest possible one. The algorithm of the updated procedure was based on the Box-Wilkinson's orthogonal multi - factorial experimental design. The updated model outputs were represented as the governing equations which were used to predict the time intervals between any two chosen characteristic points, specified in the unique drying theory, as a function of the drying air parameters. These equations were valid for any value of the drying air parameters taken from the previously established limiting boundary range. The updated procedure was compared with the original one for two predefined drying air parameters sets. Regardless to the fact that in the first case the results were not experimentally obtained they were similar to those which were in the second case experimentally identified. This was additional confirmation that the same quality degree has been maintained in both procedures, despite the fact that the total number of experiments was lower in the upgraded procedure than in the original one.

Keywords: *dryer optimization, drying porous media, effective diffusion coefficient, clay tile, software*

1. Introduction

Drying represents a common unit operation in the brick and tile industry. It is an energy intensive process which has enormous influence on the resulting product quality. The rational use of the available energy capacities as well as the usage of energy efficient one has become one of the priorities in the modern society. Even though it is difficult to compare and make a sharp distinction between the various drying technologies applied in the brick and tile sector transition toward the better operational strategies and efficient control of the dryers is continually registered. During drying the moisture is transported from inside of the green clay porous products (bricks or tiles) up to its surface. A comprehensive explanation of the registered simultaneous heat and mass process requires the use of multidisciplinary approach. In other words modeling is inherently a coupled and complex problem in which both transports in air and in the porous material has to be taken.

The starting set of partial differential equations can be overcame at three complexity levels (conjugate degrees), using four calculation procedures: diffusion [1-3, 14], receding front [4,5], macroscopic continuum technique (for coupled multiphase heat and mass transport inside the porous materials) [6,7] and pore network routine [8-10]. The conjugate degree represents the level in which heat and mass transport in air and in the porous materials are solved simultaneously in a transient way. For example at the conjugate modeling degree the flow field is solved using boundary-layer or Navier-Stoks equations [11].

The general procedure specially designed to support the tendency for energy efficient drying in the clay and tile sector was recently validated and reported [12]. It was harmonized with the current observations expressed in the theory of moisture migration during isothermal drying. According to this approach all possible mechanisms of moisture transport and their transitions from one to another during isothermal drying, within a green clay products, are visible on the curve effective moisture diffusivity vs. moisture content or drying time [13]. Modeled drying regime is composed of five isothermal segments.

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Durations of previously mentioned drying segments were taken from the relevant Deff – MR curves.

2. Material and methods

Two raw materials, designated as A and B, were used in this study. They were obtained from local Serbian roofing tile producers. Raw materials were dried at 60^0C and then were broken into pieces in a laboratory perforated rolls mill. After that, smashed material was at the same time moisturized and milled down using the laboratory differential mills. Roofing tile samples (120 x 50 x 14 mm) were formed in the Laboratory extruder "Hendle" type 4, under a vacuum of 0.8 bar.

Specially constructed laboratory dryer, equipped with the balance and extensometer was used in this study. Its design has allowed us to achieve a stable regulation of the wet drying air parameters during drying, within the range of 0-120 °C, 20-100 % and 0-3.5 m/s with accuracies of ±0.2 °C, ±0.2 % and ±0.1 % for temperature, humidity and velocity~~,~~ respectively. Schematic view of the previously mentioned laboratory dryer is given in Fig.1. Green roofing tile mass as well as its linear shrinkage were continually monitored and recorded during drying. The accuracies of these measurements were 0.01 g and 0.2 mm, respectively.

Let us imagine for a moment a multidimensional space. For example in the Cartesian coordinate system the imagined space would be a box. This space can interact with its surroundings. Only two interaction types are possible. Interactions directed towards the imagined surface and the one directed from it. Previously stated interactions are respectively called "input" and "output (response)" factors. The polynomial equation (1) which provides the relation between the output and input factors is usually called the response function. This equation represents a mathematical description of the characteristic interaction surface in a multidimensional space. It is a common practice that the space in which the response surface exists is called factorial space. If k represents the total number of input factors than the equation (1) is characterizing the response surface in k+1 measurements space. It is important to state that the factorial space has its limiting boundary range. In other words the minimal and maximal values of each input factors are defining only one characteristic interaction surface for which equation (1) is valid. Box-Wilkinson orthogonal multi-factorial experimental design method is based on the previously mentioned statement. It was used for defining the minimal number of experiments which are necessary for adequate identification of the characteristics interaction surface and reliable determination of the response function.

$$y = b_0 + \sum_{i=1}^{k} b_i x_i + \sum_{i<j}^{k} b_{ij} x_i x_j + \sum b_{ii} x_i^2 + \cdots \quad (1)$$

The algorithm of the updated procedure for heavy clay dryer optimization was based on the formerly mentioned model. After the experimental matrix was set up, previously presented procedure [13] was applied for each planed experiments. Obtained data were used to calculate the duration of the characteristic isothermal segments which represents the model output factor y. Parameter sets x_1, x_2..., x_i and b_0, b_i, b_{ij} were representing respectively the model input factors (drying air velocity, temperature and humidity) and its corresponding regression coefficients. Kohren and Fisher [15] criteria were used for statistical assessment of the experimental reproducibility and model evaluation. All calculations as well as data analysis was realized with the fully licensed version of the commercial Minitab 15 software package.

According to the Box-Wilkinson method the minimal number of experiments which were necessary for accurate and reliable determination of the response function is closely related with the number of input factors. In our case this number is, for the fully factorial experimental matrix with three input parameters, specified as eight. Even though we need 8 different isothermal experiments, in order to satisfy statistical criteria for experimental

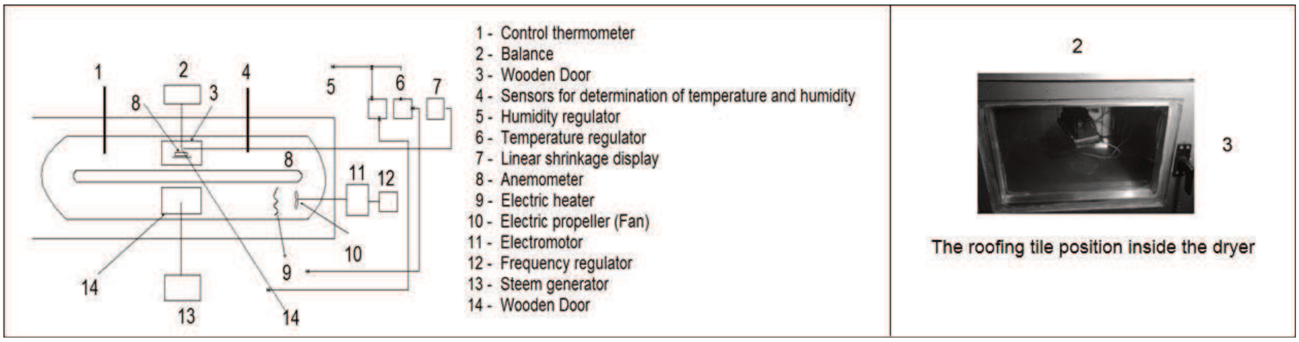

Fig. 1 - Schematic view of laboratory recirculation dryer.

Table 1

Drying air parameters – isothermal drying

Exp.	Air velocity, *W* / m/s	Air temperature, *T* / °C	Air humidity, *V* / %
1 & 9	1	20	60
2 & 10	3	20	60
3 & 11	1	20	85
4 & 12	3	20	85
5 & 13	1	45	60
6 & 14	3	45	60
7 & 15	1	45	85
8 & 16	3	45	85

Table 2

Drying air parameters - proposed drying regimes.

Exp.	Segment														
	I (0-C)			II (C-D)			III (D-E)			IV (E-F)			V (90)		
	%	^{0}C	m/s	%	^{0}C	m/s	%	^{0}C	m/s	%	^{0}C	m/s	%	^{0}C	m/s
17	85	35	1.0	70	40	1.5	65	40	2.0	60	45	2.5	50	70	3
18	80	30	1.0	70	35	1.5	70	40	2.0	70	45	2.5	60	70	3

reproducibility it is necessary to repeat those experiments at least once more, so the real number of experiments is 16. Drying air parameters which were maintained constant during drying, for our experimental matrix, are presented in Table 1. Drying air parameters, which remained constant in each characteristic segment, of the proposed industrial drying regimes, are presented in Table 2. The original procedure for heavy clay dryer optimization stated in the reference [12] was recently successfully applied in the roofing factory A. That regime was identical as the one designated in table 2 as Exp. 17.

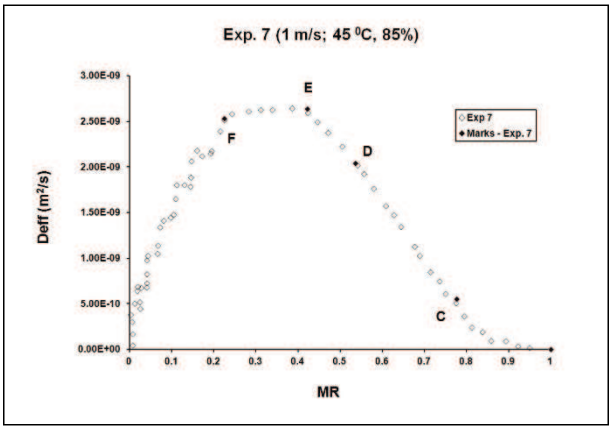

Fig. 2 - Typical Deff - MR curve.

3. Results and discussion

The unique drying theory was developed five years ago and has recently won a general recognition in the scientific community. According to this theory all possible mechanisms of moisture transport and their transitions from one to another during isothermal drying, within a green clay products, are visible on the curve effective moisture diffusivity vs. moisture content or drying time. Typical curve which represents the dependence of the effective moisture diffusivity as a function of the moisture content is presented in the reference [13] as Fig.3. Deff - MR curve presented in this paper as Fig.2 was given as an example. This curve was calculated from the data registered in isothermal experiment 7. The other curves were not presented due to the lack of the space. It can be seen that the shape of the Fig. 2 is similar with the typical Deff-MR curve.

It is important to emphasize that only moisture transport mechanisms and their transitions (characteristic points) registered on the corresponding Deff - MR curves, up to the "lower critical" point F, were used for modeling the industrial drying regimes. That is the reason why only four characteristic points were additionally marked with bold letters on the Fig. 2. These points were summarized in Table 3. Identified characteristic points detected for each planed experiment (Exp.1 - 16) and for both raw materials (A and B) were presented in Table 4.

According to the original procedure, for heavy clay dryer optimization, the proposed drying regime is consisted of five isothermal drying segments. Interval registered on the corresponding Deff – MR curve, from its starting point O up to the characteristic point C, defines the first dying segment. The moisture transport from the material surface in this segment is restrained and limited. Characteristics intervals CD, DE and EF registered on the corresponding Deff - MR curves were representing respectively other three drying segments. Duration of the fifth segment was limited to 90 minutes. During the second drying segment the external and internal moisture transport has to be elevated and adjusted in such way that the drying surface remains fully covered by a water film. The air parameters in the third segment are carefully chosen to allow, that during the transition dying period, the partially wet

Table 3

Possible drying mechanisms according to reference [12] up to lower critical point

Drying segment	Transport of liquid water	Transport of vapor
A B	Capillary pumping flow (CPF) through the biggest capillaries	/
B C	CPF through macro capillaries, HF	/
C D	CPF through mezzo capillaries, HF	/
D E	CPF (from capillaries in funicular state),HF and liquid diffusion in the pores	hydrodynamic flow (HF)
E F	Creeping along the capillary when the liquid is in the funicular state or by the successive evaporation – condensation mechanism between liquid bridges.	HF (difference in total pressure)
0A - Initial period / AE - Constant period / DF – transition period / FL - Falling period D - "upper critical" point; F - "lower critical" point /		

Table 4

Characteristic data registered from point A up to point F for both raw materials

Exp.		t (min) / MR					
		A	B	C	D	E	F
1	A	42 / 0.990	105 / 0.889	165 / 0.779	260 / 0.552	318 / 0.469	475 / 0.283
	B	50 / 0.991	115 / 0.892	185 / 0.783	285 / 0.559	330 / 0.472	520 / 0.275
2	A	30 / 0.990	88 / 0.890	130 / 0.780	220 / 0.554	255 / 0.470	410 / 0.285
	B	40 / 0.992	98 / 0.892	145 / 0.775	245 / 0.559	280 / 0.476	450 / 0.290
3	A	68 / 0.985	170 / 0.877	282 / 0.772	415 / 0.542	515 / 0.430	781 / 0.227
	B	75 / 0.990	180 / 0.881	300 / 0.778	430 / 0.549	520 / 0.440	798 / 0.230
4	A	60 / 0.989	145 / 0.882	250 / 0.775	365 / 0.548	462 / 0.425	668 / 0.222
	B	70 / 0.992	155 / 0.886	260 / 0.779	375 / 0.551	482 / 0.434	692 / 0.225
5	A	21 / 0.991	70 / 0.884	114 / 0.772	175 / 0.542	220 / 0.447	330 / 0.256
	B	25 / 0.988	80 / 0.886	128 / 0.769	188 / 0.547	240 / 0.449	360 / 0.254
6	A	14 / 0.982	45 / 0.877	82 / 0.767	140 / 0.538	159 / 0.462	242 / 0.275
	B	20 / 0.984	55 / 0.879	95 / 0.771	156 / 0.541	169 / 0.463	260 / 0.278
7	A	60 / 0.991	130 / 0.879	218 / 0.777	315 / 0.537	400 / 0.422	590 / 0.225
	B	70 / 0.988	145 / 0.881	235 / 0.774	350 / 0.532	450 / 0.426	620 / 0.229
8	A	50 / 0.989	108 / 0.865	182 / 0.771	273 / 0.528	335 / 0.419	483 / 0.222
	B	70 / 0.983	125 / 0.870	199 / 0.776	293 / 0.535	350 / 0.428	535 / 0.229
9	A	43 / 0.991	106 / 0.888	164 / 0.780	261 / 0.551	317 / 0.470	474 / 0.284
	B	49 / 0.992	116 / 0.891	184 / 0.782	286 / 0.558	329 / 0.473	519 / 0.276
10	A	31 / 0.991	89 / 0.889	131 / 0.781	221 / 0.553	254 / 0.471	409 / 0.286
	B	39 / 0.993	99 / 0.891	146 / 0.774	244 / 0.560	279 / 0.477	449 / 0.291
11	A	69 / 0.984	171 / 0.876	281 / 0.773	414 / 0.543	514 / 0.431	782 / 0.228
	B	74 / 0.989	179 / 0.880	299 / 0.777	429 / 0.550	521 / 0.439	799 / 0.231
12	A	61 / 0.988	144 / 0.881	251 / 0.776	366 / 0.549	463 / 0.424	669 / 0.223
	B	69 / 0.991	154 / 0.885	261 / 0.778	376 / 0.550	483 / 0.433	693 / 0.226
13	A	22 / 0.992	69 / 0.883	113 / 0.773	176 / 0.541	221 / 0.446	331 / 0.257
	B	24 /0.989	81 /0.885	127 / 0.768	1870 / 546	241 / 0.448	361 / 0.255
14	A	15 / 0.983	46 / 0.876	83 / 0.768	139 / 0.539	160 / 0.461	243 / 0.276
	B	21 / 0.985	56 / 0.878	96 / 0.770	155 / 0.542	168 / 0.462	261 / 0.279
15	A	61 / 0.992	131 / 0.880	217 / 0.778	316 / 0.538	399 / 0.421	589 / 0.224
	B	71 / 0.987	146 / 0.882	234 / 0.773	351 / 0.533	449 / 0.425	619 / 0.228
16	A	51 / 0.988	109 / 0.866	183 / 0.772	274 / 0.527	334 / 0.418	482 / 0.221
	B	71 / 0.982	126 / 0.871	200 / 0.775	292 / 0.534	349 / 0.427	534 / 0.228

surfaces provide a constant rate of drying. Within the fourth drying segment the liquid transport, which arise from the pores that still possess the moisture capacity and are around the surface "dry" patches, has to be harmonized with the liquid flow which came from the surface "wet" patches.

As it was previously stated the input parameters in the upgraded procedure, for heavy clay dryer optimization were temperature, humidity and velocity (see Table 1). The output parameters were respectively the duration of the characteristic intervals OC, CD, DE and EF. These parameters were easily computed, for each planed experiment, from the formerly determined records (see Table 4). It is important to state that each output parameter is defining only one response equation. In our case the final model results will be represented with four response equations. The response model equations are only valid for the values of the drying air parameters that are within the boundary range specified in the corresponding experimental matrix (see Table 1). The estimated regression coefficients are presented in the Table 5. Each model equation was statistically evaluated. Results presented in table 6, are pointing out that the corresponding equations can be safely used for accurate prediction of the

Table 5

Estimated regression coefficients for the proposed drying regimes

independent variables - factors	Estimated regression coefficient for clay A			
	t (0-C)	t (C-D)	t (D-E)	t (E-F)
Constant	-65.520	-4.440	28.280	-283.42
Temperature	-2.044	1.372	-3.664	8.196
Humidity	4.732	2.044	0.872	7.592
Velocity	-17.820	-6.600	-17.680	64.74
Temperature*Humidity	0.010	-0.027	0.046	-0.1296
Temperature*Velocity	0.396	-0.460	0.824	-2.612
Humidity*Velocity	-0.148	-0.180	0.208	-1.304
Temperature*Humidity*Velocity	-0.006	0.008	-0.014	0.0352
independent variables - factors	Estimated regression coefficient for clay B			
	t (0-C)	t (C-D)	t (D-E)	t (E-F)
Constant	-35.720	71.340	-5.780	-198.520
Temperature	-1.844	0.648	-3.436	8.336
Humidity	4.712	0.876	0.668	7.272
Velocity	-24.580	-63.300	-7.820	101.160
Temperature*Humidity	0.002	-0.013	0.062	-0.150
Temperature*Velocity	0.284	0.520	0.676	-4.528
Humidity*Velocity	-0.112	0.700	0.412	-2.216
Temperature*Humidity*Velocity	-0.002	-0.008	-0.022	0.073

Table 6

Statistical parameters for models evaluation

Model validation for Clay A	t (0-C)	t (C-D)	t (D-E)	t (E-F)
R-Sq / %	99.99	99.91	99.92	99.99
R-Sq(pred) / %	99.98	99.64	99.67	99.98
R-Sq(adj) / %	99.99	99.83	99.84	99.99
Model validation for Clay B	t (0-C)	t (C-D)	t (D-E)	t (E-F)
R-Sq / %	99.99	99.89	99.95	99.98
R-Sq(pred) / %	99.98	99.56	99.79	99.96
R-Sq(adj) / %	99.99	99.79	99.90	99.97

Note:
R-Sq – is representing the probability of correlation coefficient accuracy.
R-Sq (pred) – is representing the model prediction accuracy.
R-Sq (adj) – is representing the adjusted model prediction accuracy. This model accuracy is including the correction which is related on the number of model parameters.

Table 7

Duration of the proposed drying regimes

Exp.	t (0-C)		t (C-D)		t (D-E)		t (E-F)		V
	OR	UP	OR	UP	OR	UP	OR	UP	
17	262	262.9	93	94.6	41	41.8	99.8	101	90
18	259	260.9	101	100.4	52	51.2	144.6	143.4	90
Note	OR – original procedure / UP – upgraded procedure								

characteristic drying segment duration. Previously mentioned equations were used for modeling the kinetic of the proposed drying regimes (Exp. 17 and 18).

The updated procedure was compared with the original one for two predefined proposed drying air parameters sets. Estimated duration of the characteristic drying segments for both proposed drying regimes were presented in the Table 7.

Regardless to the fact that in the first case (UP) the final modeling results were not experimentally identified they were similar to the values which were in the second case (OR) experimentally determined (see table 7). This was additional confirmation that the same quality degree has been maintained in both procedures, despite the fact that the total number of experiments in the upgraded procedure was lower than in the original one.

4. Conclusion

Two main barriers for broader application of the original procedure, for setting up the drying regime, that is consistent with the theory of moisture migration, were identified. The first one is related with the fact that this method requires huge Deff - MR data base which is created from a large number of isothermal experiments. The second barrier is associated with the time to process the formerly mentioned data base. In order to overcome observed model disadvantages the procedure upgrade was proposed. Box-Wilkinson's orthogonal multi-factorial experimental design was chosen as the most suitable mathematical tool for estimation of any characteristic isothermal drying segment duration as a function of the drying air parameters. Four mathematical equations were developed. These simple equations were valid for any values of the drying air parameters that were in the range defined by the experiment matrix. The updated procedure was compared with the original one for two predefined proposed drying air parameters sets. Results were similar even though the total number of experiments in the upgraded procedure was lower.

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REFERENCES

1. G. Efremov and T. Kudra.: „Calculation of the Effective Diffusion Coefficients by Applying A Quasi-Stationary Equation for Drying Kinetics", Drying Technology, Vol. 22, 2004, **10**, 2273.
2. W.P. Silva, J.W. Precker, C.M.D.P.S Silva, D.D.P.S. Silva.: „Determination of the effective diffusivity via minimiyation of the objective function by scanning:Application to drying of cowpea", Journal of Food Engineering, 2009, **95**, 298.
3. I.I Ruiz-Lopey and M.A. Garcia-Alvarado.: „Analytical solution for food-drying kinetics considering shrinkage and variable diffusivity", Journal of Food Engineering, 2007, **79**, 208.
4. A.V. Luikov.: „System of differential equations of heat and mass transfer in capillary-porous bodies (review) ", International Journal of Heat and Mass Transfer, 1975, **18**(1), 1.
5. A. Hashimoto, S. Stenstrom, T. Kameoka.: „Simulation of convective drying of wet porous materials", Drying Technology, 2003, **21**(8), 1411.
6. S. Whitaker.: „Coupled transport in multiphase systems: A theory of drying„ Advances in Heat Transfer", 1998, **31**, 1.
7. T.H.Vu.: „Influence of Pore Size Distribution on Drying Behaviour of Porous Media by a Continuous Model", (Phd), Otto-von-Guericke-University Magdeburg, (2006).
8. T.Metzger and E.Tsotsas.: „Influence of pore size distribution on drying Kinetics: A simple Capillary Model", Drying Technology, 2005, **23**(9-11) 1797.
9. Y. Yuejin, Z. Zhe, N. Junnan and X. Yingying.: „Pore Network Analysis of Zone Model for Porous Media Drying", Mathematical Problem in Engineering, http://dx.doi.org/10.1155/2014/624145, (2014)
10. G. A. Yiotis, N.I. Tismpanogiannis, K.A. Stubos and C.Y. Yortsos.: „Pore network study of the characteristic periods in the drying of porous materials", Journal of Colloid and Interface Science, 2006, **297,** 738..
11. T. Defraeye, B.Blocken, D.Derome, B.nicolai and J. Carmeliet.: „Convective heat and mass transfer modeling at air-porous material interfaces:overview of existing methods and relevance", Chemical Engineering Science, 2012, **74**, 49.
12. M. Vasić, R. Rekecki and Z. Radojević.: „Procedure for setting up the drying regime that is consistent with the nature and properties of the clay raw material", Drying Technology, 2018, **36**(3), 267.
13. M. Vasić, Ž. Grbavčić. Z. Radojević.: „Analysis of moisture transfer during the drying of clay tiles with particular reference to an estimation of the time-dependent effective diffusivity", Drying Technology, 2014, **32**, 829..
14. M.Vasić, Z.Radojević, M.Arsenović, Ž. Grbavčić.: „Determination of the effective diffusion coefficient", Romanian Journal of Materials, 2011, **42**(2), 169.
15. M. Lazić.: "Elements of Mathematics II", An imprint, Faculty of Technology and metallurgy, University of Belgrade, 1990.

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MANIFESTĂRI ȘTIINȚIFICE / SCIENTIFIC EVENTS

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