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ABSTRACT

Along with the widely use in industries and lives, the dehumidification systems have consumed a large amount of energy. Fortunately, the application of liquid desiccant dehumidification system can greatly reduce the consumption of high-grade energy. To improve the advantages of liquid desiccant system compared with the conventional dehumidification system, one of the key measures is to increase the efficiency of the regeneration sub-system. In this study, models for the regeneration tower and counter-current heat exchanger, which are recognized by previous experiments, are employed and the corresponding VC++ computer program modules are used to describe the heat and mass transfer processes between the liquid desiccant solution and moist air in the regenerator and the heat transfer process in heat exchanger respectively. The orthogonal design is used to arrange the numerical experiment. The results are analyzed by the method of variance analysis to determine the relative significance of operating parameters and the interactions between them. The analysis on the influence factors shows that for the evaporation rate of water vapor in the regenerator, the important parameters are the inlet temperature and concentration of the solution, the mass flow ratio of dry air to dehydrated desiccant, and the NTU of the regenerator. The analysis also shows that for the regeneration efficiency, the important parameters are the mass flow ratio of dry air to dehydrated desiccant, the NTU of the regenerator and the inlet temperature of solution. There is no interaction that influences the evaporation rate of water vapor and the regeneration efficiency significantly.

1. INTRODUCTION

The dehumidification systems have been widely used in industrial and agricultural production and people's lives. Every year a large quantity of energy is consumed to dehumidify the raw materials and end products in industrial and agricultural production (Lowenstein, 2005). Besides, dehumidification plays an important role in making a healthy and comfortable environment for work and life. Unlike the conventional air conditioning system, liquid desiccant dehumidification system, based on its high affinity for water vapor, can directly dehumidify the moist air without lowering the air temperature to its dew point. In this way, the application of liquid desiccant dehumidification system can greatly reduce energy consumption.

Since the liquid desiccant dehumidification system was proposed by Löf (1955), this technique has gone through a long-term development. A key measure to highlight the virtue of this system is to increase the efficiency of its regeneration subsystem. At present, the most widely studied are packed tower regenerator (Pumo and Goswami, 2002; Ani *et al*., 2005; Sultan *et al*., 2002; Sanjeev *et al*., 2000; Ertas *et al*., 1994), internal heating regenerator (Yin *et al*., 2007; Yin *et al*., 2008) and solar collector/regenerator (Peng and Howell, 1984; Li and Yang, 2008). In these previous literature, the respective influences of various system parameters on the regenerator's performance are analyzed, including the system operating parameters (like the inlet temperature, concentration and mass flow of dilute solution, and the inlet temperature and moisture content and mass flow of regeneration air) and the system structure parameters (like packing height and the length of C/R). Among these analyses, nevertheless, there is none that has pointed out which parameter has the key influence on the evaporation rate of water vapor in regenerator, which parameter has the key influence on the regeneration efficiency and whether there is any interaction among these parameters.

In this paper, two models, the one-dimensional model of coupled heat and mass transfer in packed tower verified in experiment (Ren *et al*., 2006) and the model of countercurrent heat exchanger (Yang and Tao, 1998), are adopted to describe respectively the heat and mass transfer process of the solution and air in regeneration tower and the process of countercurrent heat exchange in the air to air heat exchanger. There follows an analysis of the data obtained in the numerical experiment by the method of orthogonal design to inspect the importance of each factor and whether there is interaction between them. This analysis is expected to work as a further effort to clarify the research ideas about the regeneration subsystem and thus help researchers set priorities in both their following experiment and simulation researches.

2. MODEL OF REGENERATION SUBSYSTEM

2.1 Model of Regeneration Tower

The regeneration subsystem is shown in figure 1. In this subsystem, the model of regeneration tower is described in the one-dimensional governing equations of coupled heat and mass transfer (Ren *et al*., 2006), and the process of heat and mass transfer in the small section of this tower is shown in figure 2.

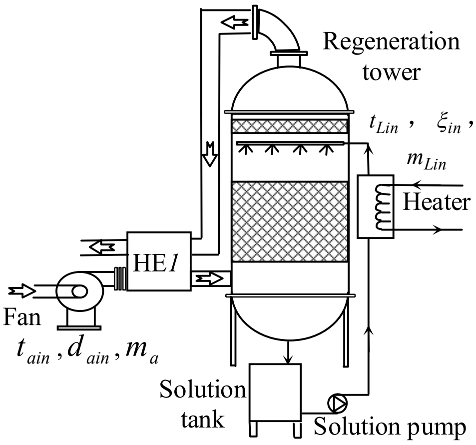

Figure 1: Schematic of regeneration subsystem

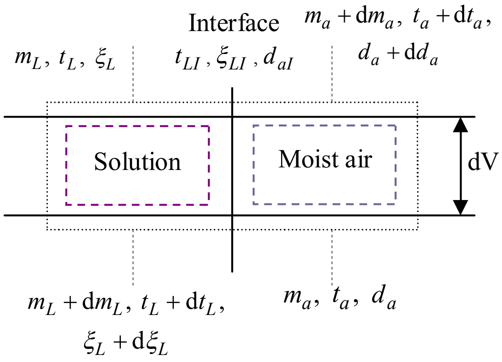

Figure 2: Schematic of heat and mass transfer process in a small section of the dehumidification tower

After transforming the parameters in equation (2)， (11)-(14) in the reference (Ren *et al*., 2006), governing equations of the heat and mass transfer process in regenerator tower can be obtained like the equation (1)-(5) in reference (Tu *et al*., 2009). These governing equations are shown as below:

$$\mathrm{d}d_a = (d_a - d_{eL})(1/Le)\mathrm{d}NTU_{\mathrm{Re}g} \tag{1}$$

Where, d_a indicates the moisture content of the humid air, kg/(kg.d.a); d_{eL} indicates the moisture content of humid air in equilibrium with the solution, kg/(kg.d.a); Le indicates Reynolds number; $NTU_{\mathrm{Re}g}$ indicates the number of heat transfer unit in the regeneration tower.

$$\mathrm{d}\xi = 1.608(d_a - d_{eL})\frac{R_m\xi^2}{Le\left[\left(2R^2{}_{dw} - 2R_{dw}\right)\xi - 2R^2{}_{dw} + R_{dw}\right]}\mathrm{d}NTU_{\mathrm{Re}g} \tag{2}$$

In this equation, ξ indicates mass concentration of the solution, %; R_m indicates the molar flow rate ratio of the dry air and solute, $R_m = (m_a M_d)/(m_d M_a)$; m_a and m_d indicate respectively the mass flow rate of the air and solute, kg/s; M_a and M_d indicate respectively the molecular weight of the air and solute, kg/kmol; R_{dw} indicates molecular weight ratio of the solute and water, $R_{dw} = M_d / M_w$; M_w indicates the molecular weight of water, kg/kmol.

$$\mathrm{d}t_a = (t_a - t_L)\frac{Le - 1.608R_{va}(d_a - d_{eL})}{Le(1 + 1.608d_a R_{va})}\mathrm{d}NTU_{\mathrm{Reg}} \tag{3}$$

In this equation, t_a indicates the air temperature, $^{\mathrm{o}}$C; t_L indicates the solution temperature, $^{\mathrm{o}}$C; R_{va} indicates the ratio of molar specific heat at constant pressure between water vapor and dry air, $R_{va} = (M_w C_{pv})/(M_a C_{pa})$; C_{pa} and C_{pv} indicates respectively the specific heat at constant pressure of dry air and water vapor, kJ/(kg $^{\mathrm{o}}$C).

$$\mathrm{d}t_L = C^*[(t_a - t_L) + 1.608(\widetilde{h}_s / Le)(d_a - d_{eL})]\mathrm{d}NTU_{\mathrm{Reg}} \tag{4}$$

In this equation, C^* indicates the ratio of heat capacities between the air and solution; $\widetilde{h}_s$ indicates the standardized heat of absorption, $\widetilde{h}_s = (M_w h_s)/(M_a C_{pa})$, $^{\mathrm{o}}$C; h_s indicates the heat of absorption, kJ/kg.

$$\mathrm{d}m_L = -m_a \mathrm{d}d_a \tag{5}$$

Where, m_L indicates the mass flow rate of the solution, kg/s.

The boundary conditions of governing equations (1)-(5) are shown as below:

$NTU_{\mathrm{Reg}} = NTU0$, $t_L = t_{Lin}$, $\xi = \xi_{in}$, $m_L = m_{Lin}$

$NTU_{\mathrm{Reg}} = NTUn$, $t_a = t_{ain}$, $d_a = d_{ain}$

Where, $NTU0$ indicates the number of heat transfer unit at the top of the regeneration tower ($NTU0$=0 this moment), $NTUn$ indicates the heat transfer unit number from the top of the tower to its bottom; $t_{Lin}, \xi_{in}, m_{Lin}$ indicates the temperature, mass concentration and mass flow rate of the solution when it enters the regeneration tower from the top; t_{ain}, d_{ain} indicates the temperature and moisture content of the air when it enters the regeneration tower from the bottom, and the subscript "in" indicates the suction parameter.

2.2 Model of Heat Exchanger

In the regeneration subsystem an air to air heat exchanger is adopted. As is shown in figure 1, the hot and cold fluid flow direction in heat exchanger HE*1* are countercurrent, so the method of $\varepsilon - NTU$ can be used to expediently calculate the respective outlet temperature of the hot and cold fluid. There are two steps of this method: firstly, define the number of heat transfer unit (NTU_{HE}); secondly compare the heat capacity of these two fluids, $m_h C_h$ and $m_c C_c$, and define the big one as $(mC)_{\max}$ and the small one as $(mC)_{\min}$. The efficiency formula of the heat exchanger can be obtained as follow (Yang and Tao, 1998):

$$\varepsilon_{HE} = \frac{1 - \exp\{(-NTU_{HE})[1 - \frac{(mC)_{\min}}{(mC)_{\max}}]\}}{1 - \frac{(mC)_{\min}}{(mC)_{\max}}\exp\{(-NTU_{HE})[1 - \frac{(mC)_{\min}}{(mC)_{\max}}]\}} \tag{6}$$

In this formula, ε_{HE} indicates the heat exchange efficiency of the heat exchanger.

The whole heat exchange capacity in the heat exchange process is as below:

$$Q_{HE} = \varepsilon_{HE}(mC)_{\min}(t_{hin} - t_{cin}) \tag{7}$$

In this formula, t_{cin} and t_{hin} indicate respectively the inlet temperature of the cold and hot fluid, ℃.

The outlet temperature of the hot fluid is:

$$t_{hout} = t_{hin} - \frac{Q_{HE}}{m_h C_h} \tag{8}$$

The outlet temperature of the cold fluid is:

$$t_{cout} = t_{cin} + \frac{Q_{HE}}{m_c C_c} \tag{9}$$

Tu *et al.* (2009) described the model of regeneration tower and the model of countercurrent air-air heat exchanger successfully by using the VC++ language simulation modules. These stimulation modules are still adopted in this paper to study the impact of several related factors on the performance of the regeneration subsystem.

3. EXPERIMENTAL INDEXES AND METHODS

3.1 Experimental Indexes

With reference to relevant literature (Pumo and Goswami, 2002; Yin *et al.*, 2007), the experimental indexes of the regeneration subsystem in this paper are defined as the water evaporation rate in regeneration tower m_{evap} and its regenerative efficiency $\varepsilon_{\mathrm{Re}g}$. Their definition formulae are shown as below:

$$m_{evap} = (d_{aout} - d_{ain}) m_a \tag{10}$$

Where, d_{aout} and d_{ain} indicate respectively the air moisture content of the outlet and inlet in the regeneration tower, kg/(kg.d.a).

$$\varepsilon_{\mathrm{Re}g} = \frac{d_{aout} - d_{ain}}{d_{eLin} - d_{ain}} \tag{11}$$

In equation (11), d_{eLin} indicates the moisture content of the humid air which is in equilibrium with the inlet solution, kg/(kg.d.a).

3.2 Experimental Design and Analysis Method

Firstly, the numerical experiment in this paper is arranged by the method of orthogonal design; then the experiment result is analyzed by the method of variance analysis to determine the respective importance of each factor.

Orthogonal design is an optimized experimental design method used in multi-factor and multi-level experiment. It is adopted in this paper to choose some representative ones from all the treatment combinations for the experiment, thus relieving the burden of doing a large quantity of multi-factor comprehensive experiments and the difficulty in controlling experiment conditions (Liu, 2005).

Variance analysis is a statistical method used to determine whether there exists a significant performance difference among the levels of a factor. Through data analysis by means of this method, those factors can be picked out which play a key influence on the object, the interactions among them and the optimal level of each factor (Hu and Wang, 2006).

4. FACTOR ANALYSIS

4.1 Screening Analysis of Factors

Before the process of screening, seven influence factors are picked out. In order to reduce the number of experiments, only two levels of each of these factors are chosen. According to the rules, one level is in the central position, and the other is near the boundary. Factor level of the central position is the optimal value based on the existing expertise and experience. The seven factors and their levels are shown in Table 1.

Table 1 The values of the two levels for the seven influence factors

Levels	**Factors**						
	t_{Lin} [°C]	ξ_{Lin} (wt% salt)	t_{ain} [°C]	d_{ain} [kg/kg.d.a]	m_{ain}/m_d [kg/kg]	NTU_{Reg}	NTU_{HE}
1	50	32%	26.0	0.01279	1.185	1.0	1.0
2	70	38%	30.5	0.01672	2.843	3.0	3.0

Orthogonal table $L_{12}(2^{11})$ is used to arrange the orthogonal experiments, and the arrangement and results of the selection experiment are shown in figure 2.

Through the variance analysis of the experimental data, P value of each factor can be obtained. P value is a probability value, which shows the error probability based on the belief that there exists a significant performance difference among the levels of a factor. A small P value indicates great significance of this factor and vice versa. The detailed relation between P value and the significance of a factor is as follows: when $0 \le P$ value≤ 0.01, the factor is highly significant and very important; when $0.01 < P \le 0.05$, the factor is significant and important; when $0.05 < P \le 0.2$, the factor has a weak significance and a faint influence on the experimental results; when $0.2 < P \le 1$, the factor is insignificant and has no influence on the experimental results.

Through the variance analysis of the experimental results of the water evaporation rate in the regeneration tower m_{evap} and its regeneration efficiency $\varepsilon_{\mathrm{Reg}}$, the results are obtained, which are shown in figure 3 and figure 4 respectively.

When the water evaporation rate of the regeneration tower m_{evap} acts as an experimental index, from Table 3 it is obtained that the P value of t_{Lin} is less than 0.01. By referring to the relation between the P value and the significance of factors, t_{Lin} is evaluated as highly significant for m_{evap}; the P values of ξ_{Lin}, m_a/m_d, and NTU_{Reg} range from 0.01 to 0.05, which indicates these three factors are significant and can be valued as important factors; the P values of d_{ain}, t_{ain} and NTU_{HE} are all above 0.2, which indicates these three factors are insignificant and have faint influence on the experimental results. These seven factors are arranged in descending order based on their respective influence on m_{evap} (or their respective P value in ascending order) like this: t_{Lin}, m_a/m_d, ξ_{Lin}, NTU_{Reg}, d_{ain}, NTU_{HE}, t_{ain}.

Table 2 Arrangement of the orthogonal experiment with $L_{12}(2^{11})$ and the experiment results

Column number	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**Results**	
Factors	t_{Lin}	ξ_{Lin}	t_{ain}	d_{ain}	m_a / m_d	$NTU_{\mathrm{Re}g}$	NTU_{HE}						
Experiment number												m_{evap}	$\varepsilon_{\mathrm{Re}g}$
1	1(50)	1(32%)	1(26.0)	1(0.01279)	1(1.185)	1(1.0)	1(1.0)	1	1	1	1	0.00363	0.5350
2	1(50)	1(32%)	1(26.0)	1(0.01279)	1(1.185)	2(3.0)	2(3.0)	2	2	2	2	0.00573	0.8433
3	1(50)	1(32%)	2(30.5)	2(0.01672)	2(2.843)	1(1.0)	1(1.0)	1	2	2	2	0.00557	0.4320
4	1(50)	2(38%)	1(26.0)	2(0.01672)	2(2.843)	1(1.0)	2(3.0)	2	1	1	2	0.00123	0.3543
5	1(50)	2(38%)	2(30.5)	1(0.01279)	2(2.843)	2(3.0)	1(1.0)	2	1	2	1	0.00469	0.6070
6	1(50)	2(38%)	2(30.5)	2(0.01672)	1(1.185)	2(3.0)	2(3.0)	1	2	1	1	0.00119	0.8237
7	2(70)	1(32%)	2(30.5)	2(0.01672)	1(1.185)	1(1.0)	2(3.0)	2	1	2	1	0.01265	0.4653
8	2(70)	1(32%)	2(30.5)	1(0.01279)	2(2.843)	2(3.0)	2(3.0)	1	1	1	2	0.03086	0.4494
9	2(70)	1(32%)	1(26.0)	2(0.01672)	2(2.843)	2(3.0)	1(1.0)	2	2	1	1	0.02753	0.4219
10	2(70)	2(38%)	2(30.5)	1(0.01279)	1(1.185)	1(1.0)	1(1.0)	2	2	1	2	0.00962	0.4713
11	2(70)	2(38%)	1(26.0)	2(0.01672)	1(1.185)	2(3.0)	1(1.0)	1	1	2	2	0.01312	0.7038
12	2(70)	2(38%)	1(26.0)	1(0.01279)	2(2.843)	1(1.0)	2(3.0)	1	2	2	1	0.01744	0.3561

Table 3 The variance analysis table when the water evaporation rate of the regeneration tower is regarded as the experimental index

Source	**DF**	**SS**	**MS**	**F value**	**P value**
Total	11	0.001061095			
Error	4	2.75403E-05	6.88507E-06		
t_{Lin}	1	0.000663	0.000663	96.27135	0.000605
ξ_{Lin}	1	0.000125	0.000125	18.10699	0.013103
t_{ain}	1	1.41E-06	1.41E-06	0.204505	0.674548
d_{ain}	1	9.5E-06	9.5E-06	1.379462	0.305342
m_a / m_d	1	0.000143	0.000143	20.69891	0.010421
$NTU_{\mathrm{Re}g}$	1	9.06E-05	9.06E-05	13.15749	0.022212
NTU_{HE}	1	2.04E-06	2.04E-06	0.296763	0.614868

When the regeneration efficiency of the regeneration tower $\varepsilon_{\mathrm{Re}g}$ acts as an experimental index, from Table 4 it is obtained that the P values of both m_a / m_d and NTU_{Reg} are less than 0.01. By referring to the relation between the P value and the significance of factors, they are evaluated as highly significant for and having primary influence on $\varepsilon_{\mathrm{Reg}}$; the P value of t_{Lin} ranges from 0.01 to 0.05, which indicates this factor is significant and can be valued as an important factor; the P value of ξ_{Lin}, t_{ain}, d_{ain} and NTU_{HE} are all above 0.2, which indicates these four factors are insignificant and have faint influence on $\varepsilon_{\mathrm{Reg}}$. These seven factors are arranged in descending order based on their respective influence on $\varepsilon_{\mathrm{Reg}}$ (or their respective P value in ascending order) like this: NTU_{Reg}, m_a / m_d, t_{Lin}, ξ_{Lin}, NTU_{HE}, d_{ain}, t_{ain}.

Table 4 The variance analysis table when the regeneration efficiency is regarded as the experimental index

Source	DF	SS	MS	F value	P value
Total	11	0.316178671			
Error	4	0.016594699	0.004148675		
t_{Lin}	1	0.044109	0.044109	10.63212	0.03106
ξ_{Lin}	1	0.002389	0.002389	0.575825	0.49021
t_{ain}	1	9.84E-05	9.84E-05	0.023718	0.885063
d_{ain}	1	0.000311	0.000311	0.074883	0.797904
m_a / m_d	1	0.124345	0.124345	29.97226	0.005418
NTU_{Reg}	1	0.12711	0.12711	30.63864	0.005207
NTU_{HE}	1	0.001222	0.001222	0.294521	0.616161

4.2 Analysis of Interactions between Factors

By the method mentioned in section 3.1, we can also analyze the influence of the potential interactions between factors on the experimental indexes. Considering there might be a large quantity of factors plus the possible interactions between them, an orthogonal table $L_{20}(2^{19})$ is used to arrange these orthogonal experiments. As arranged, the interactions between the factors are also regarded as factors and listed on the corresponding lines among the others on the distribution table of the interactions' exceptional lines (Chen, 2009).

Through the orthogonal numerical experiment and the variance analysis, the P values of the possible interactions are obtained as follows: when m_{evap} acts as an experimental index, the P values of the interactions $t_{Lin} \times NTU_{\mathrm{Reg}}$, $\xi_{Lin} \times NTU_{\mathrm{Reg}}$, $\xi_{Lin} \times NTU_{HE}$, $d_{ain} \times NTU_{\mathrm{Reg}}$, $d_{ain} \times NTU_{HE}$, $m_a / m_d \times NTU_{HE}$ range from 0.05 to 0.2; the P values of the other interactions are all above 0.2. By referring to the relation between the P value and the significance of factors, a finding can be gained that the above six interactions have faint influence on the evaporation rate of the regeneration tower m_{evap}, and the other interactions have little influence on m_{evap}.

When $\varepsilon_{\mathrm{Reg}}$ acts as an experimental index, the P values of the interactions $t_{Lin} \times NTU_{\mathrm{Reg}}$, $t_{Lin} \times m_a / m_d$, $t_{Lin} \times NTU_{HE}$, $\xi_{Lin} \times NTU_{HE}$, $NTU_{\mathrm{Reg}} \times NTU_{HE}$, $t_{ain} \times m_a / m_d$, $d_{ain} \times NTU_{\mathrm{Reg}}$, $d_{ain} \times NTU_{HE}$, $m_a / m_d \times NTU_{\mathrm{Reg}}$ range from 0.05 to 0.2; the P values of the other interactions are all above 0.2. Therefore these nine interactions have faint influence on the regeneration efficiency of the regeneration tower $\varepsilon_{\mathrm{Reg}}$.

5. CONCLUSION

According to the above analysis, several conclusions are summarized as follows:

(1) Based on the screening analysis of the factors in regeneration subsystem of the liquid desiccant system, it is found that when different experimental indexes are chosen, there is a relatively marked difference in the importance of seven

factors, t_{Lin}, ξ_{Lin}, t_{ain}, d_{ain}, m_a/m_d, NTU_{Reg} and NTU_{HE}. When the water evaporation rate of the regeneration tower m_{evap} acts as the experimental index, t_{Lin} proves to be the most important factor, followed by ξ_{Lin}, m_a/m_d and NTU_{Reg}, which are also the important factors. And the other three factors have no significant influence on the experiment. When the regeneration efficiency $\varepsilon_{\mathrm{Reg}}$ acts as the experimental index, m_a/m_d and NTU_{Reg} prove to be the most important factors, followed by t_{Lin}, which is also an important factor. And the other four factors have little influence on the experiment.

(2) Based on the further analysis of the interactions between factors, it is found that when m_{evap} acts as the experimental index, the interactions $t_{Lin} \times NTU_{\mathrm{Reg}}$, $\xi_{Lin} \times NTU_{\mathrm{Reg}}$, $\xi_{Lin} \times NTU_{HE}$, $d_{ain} \times NTU_{\mathrm{Reg}}$, $d_{ain} \times NTU_{HE}$, $m_a/m_d \times NTU_{HE}$ have a relatively weak influence on the experiment, and the other interactions have no influence on the experiment. When $\varepsilon_{\mathrm{Reg}}$ acts as the experimental index, the interactions $t_{Lin} \times NTU_{\mathrm{Reg}}$, $t_{Lin} \times m_a/m_d$, $t_{Lin} \times NTU_{HE}$, $\xi_{Lin} \times NTU_{HE}$, $NTU_{\mathrm{Reg}} \times NTU_{HE}$, $t_{ain} \times m_a/m_d$, $d_{ain} \times NTU_{\mathrm{Reg}}$, $d_{ain} \times NTU_{HE}$, $m_a/m_d \times NTU_{\mathrm{Reg}}$ have weak influence on the experiment, and the influence of other interactions can be neglected.

(3) There is another finding based on the further analysis: whether m_{evap} or $\varepsilon_{\mathrm{Reg}}$ acts as the experimental index, t_{Lin}, m_a/m_d, NTU_{Reg} are the important influence factors; although there is no significant influence of NTU_{HE} on the two experimental indexes, it has a weak interactions with many of the other factors, which indicates NTU_{HE} has a wide range of influence; the two regeneration air inlet parameters, t_{ain} and d_{ain}, has little influence on the two experimental indexes.

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