Analysis the impact of energy storage techniques in a cold distribution system

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Abstract

This work aims to introduce the topic of energy storage, explore the types of phase change materials (organic, inorganic and eutectic), how to structure the advantages and disadvantages of each group and possible solutions that minimize or eliminate their disadvantages and analyze the possibility of implementing a cold storage system in a district cooling supply unit in order to reduce costs and save energy.

Initially it was necessary to choose the type of phase change material to the operating conditions of the water tank where the cooled water is stored which is used in urban cold chain and design a model for analyzing the dynamics of the tank with the PCM.

The material selected was a paraffin, in particular $C_{14}H_{30}$, which has the melting/solidification temperature in the range operated in the water tank.

To analyze the tank dynamics, there have been made several simulations for different options, in particular concerning the amounts of energy that was intended to store.

The variable that was emphasized, was the diameter of the spheres of the phase change material. For each amount of stored energy, this parameter was optimized. The variation were between 10 cm and 1 m3

Given the thermodynamic parameters and estimated transport properties, it was fund that upwards of 20 cm diameter, according to the results obtained by the model, PCM not totally solidifies in the used operative conditions and for the required time cycle, had not a 100 % contribution for the thermal energy storage.

The best results obtained were for 10 cm diameters for 100 % solidification and fusion of the mass of the phase change material.

Keywords: energy storage, phase change material, chilled water network, heat transfer.

1. Introduction

This paper aims to introduce the topic of energy storage. The existing types of phase change materials: organic, inorganic and eutectic. The advantages and disadvantages of each group and possible solutions to minimize or eliminate its drawback, are discussed. Store energy is a current challenge to the technologists. Not only it reduces the gap between demand and supply but also upgrades the performance of the energy systems [1] [2] [3]. Storage energy would increase the performance of power generation plants, reducing the cost.

One of the techniques of storing thermal energy is the usage of phase change materials (PCM's). In thermal energy storage, the energy from the collector is transferred to the medium. This may occur in the form of sensible heat, latent heat or both.

One major disadvantage of sensible heat storage is the large volume required, particularly when the temperature gap is small. Latent heat storage is more attractive then sensible heat storage because of its high storage density with low gap temperatures [4] [5]. However, there are several problems associated with latent heat storage due to low thermal conductivity, variation in thermo-

physical properties, subcooling and high cost [2] [3]. One of the aims of this paper is to review various phase change materials. It will help to find the appropriate PCM to insert in the water tank of CLIMAESPÇO.

2. CLIMAESPAÇO

CLIMAESPAÇO is a thermal plant located at Parque das Nações. It's a trigeneration plant, from natural gas, produces electrical energy, hot and cold energy. The water tank is described in Chapter 7, page 4.

3. Energy storage methods

There are many kinds of energy that can be stored, like mechanical, electrical and thermal energy [6].

3.1. Thermal energy storage

Thermal energy storage can be stored as sensible heat, latent heat or thermochemical, as shown in Figure 1 [3].

3.1.1. Sensible heat storage

In this type of energy, the storage is made by rising the temperature of the solid or liquid. The value of heat stored depends on the specific heat of the medium, the amount of storage material and the temperature change [4].

$$Q = \int_{T_i}^{T_f} mC_P dT = mC_P(T_f - T_i) \qquad (1)$$

It's assumed constant properties and the fact of the temperature its uniform in both states.

3.1.2. Latent heat storage

Latent heat storage is based on the heat absorption or release when the storage material changes its phase from solid to liquid or vice-versa.

$$Q = \int_{T_i}^{T_m} mC_{p,s} dT + m\gamma \Delta h_m + \int_{T_m}^{T_f} mC_{p,l} dT$$
$$Q = m\left[C_{p,s}(T_m - T_i) + \gamma \Delta h_m + C_{p,l}(T_f - T_m)\right] \qquad (2)$$

From all the thermal heat storage techniques, latent heat thermal energy is the most interesting due to its ability to have high energy storage density and the fact that it can store heat at a constant temperature that corresponds to the phase change temperature of the PCM.

Solid-solid transitions generally have small latent heat and small volume changes than solid-liquid transitions [3] [5].

Liquid-gas transition, have higher latent heat but their large volume changes rule out their potential utility in thermal storage systems [3] [5].

Solid-liquid transformations have smaller latent heat capacity than liquid-gas. Those kind of transitions have proved to be more economically viable for thermal energy storage systems.

Any latent heat energy storage system needs to possess the next characteristics:

    i.   A suitable PCM with is melting point in the desired temperature range;
    ii.   A suitable heat exchange surface;
    iii. Suitable container compatible with the PCM.

Choosing a PCM for a particular application, the operating temperature of cooling should be matched to the transition temperature of the PCM
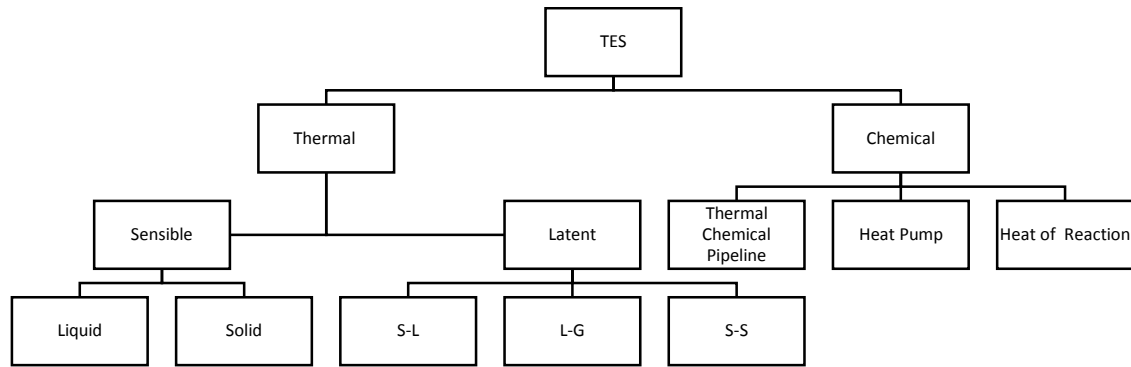
Figure 1 – Different types of thermal storage of energy.

4. Latent heat storage materials

For their usage as latent heat storage materials, PCM must have certain desirable thermodynamic, kinetic and chemical properties. Although cost and availability of these materials are also important.

4.1. Thermal Properties [3]

i.   Suitable phase transition temperature;
ii. High latent heat;
iii. Good heat transfer.

Choosing a PCM for a particular application, the

4.2. Physical Properties [3]

i.   High density;
ii. Small volume changes;
iii. Low vapor pressure.

Small volume variations on phase transformation reduces the containment problem.

4.3. Kinetic Properties [3]

i.   No supercooling;
ii. Sufficient crystallization rate.

Supercooling has been a problem aspect to some PCM, like salt hydrates. Supercooling more than a few degrees will interfere with proper heat transfer.

4.4. Chemical Properties [3]

i.   Long term chemical stability;
ii. Compatibility with materials of construction;
iii. No toxicity;
iv. No fire hazard;

PCM can suffer from chemical decomposition. They should be non-flammable and non-explosive for safety.

4.5. Economics [3]

i.   Cost effective;
ii. Available.

Low cost and large-scale availability of the PCM is a very important aspect.

5. Case study

In this paper the aim is to choose the right type of PCM due to the temperatures of the tank. In the stratified tank, the water is at temperature between 3-12 ºC. The only type of phase change material that suits these range of temperature is a paraffin [3]. The paraffin chosen was the $C_{14}H_{30}$, tetradecane.

6. PCM geometry

For the geometry to use in the phase change material we have some options: plates, cylinders or spheres. The geometry that has a higher heat transfer area is the spheres. In all simulations, the diameter of the spheres was the parameter that was changed. The tank, only with water, can retain 20 MW of energy, for a ΔT of 8 ºC and an operation time of 6 hours. The diameter had a range between 1 m and 10 cm, for each value of energy that was the goal to hold in the PCM. It was also studied the spheres to retain 10, 20, 30 and 50 % of energy that the tank can do on its own.

Table 1 – Parameters of the PCM $C_{14}H_{30}$.

Parameter	Value
ρ_S (kg/m³)	825
ρ_L (kg/m³)	771
$T_{melting}$ (°C)	4.0
$\Delta H_{melting}$ (kJ/kg)	226

The phase change material is homogeneous and isotropic with different properties to liquid and solid phase. The PCM is made by multiple spherical modules all with the same volume and are in a cylindrical container.

7. Water tank

In Figure 2 there is a diagram that represents the water tank that is subject of study in this paper.
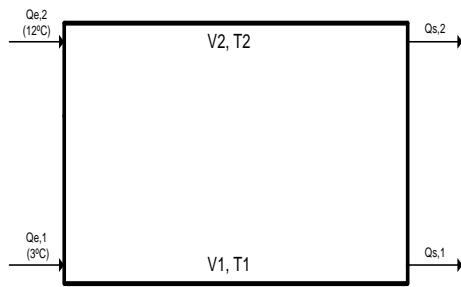
Figure 2 – Schematic diagram of the water tank without PCM.

The tank have two feeds and two outlet streams. The water that is produced in the chillers, at 3 ºC, enters the base of the tank. During the night, the charging process of cold water begins, and the volume of cold water at 3 ºC (V_1) grows. The outlet stream from the base of the tank, is the water that is distributed to the entire grid. The returning water from the grid depending on the temperature, it can enter at the top of the tank or enter into the chillers. The discharge process is made when we want to start the distribution of water V_1, so the volume decreases and the V_2 volume begins to raise. In Figure 3 there is shown the variation of cold and hot water in the tank.
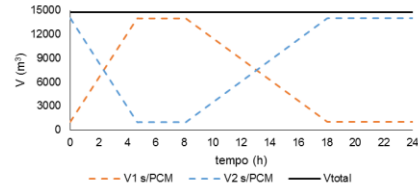

Figure 3 – Variation of cold (V_1) and hot water (V_2) in the tank.

From Figure 3, the tank gets the maximum volume of water at 3 ºC in 4 hours and 42 minutes. The discharge process has a duration of 10 hours. After this time, if the grid needs water at 3 ºC the tank can't provide it, so the chiller provides the water directly.

Table 2 – Parameters for the water tank.

Parameter	Charge process	Discharge process
$Q_{e,1}$ (m³/h)	4 000	2 500
$Q_{s,1}$ (m³/h)	1 225	3 810
$Q_{e,2}$ (m³/h)	3 000	2 500
$Q_{s,2}$ (m³/h)	5 775	1 190
$V_{1,min}$ (m³)	1 000	
$V_{2,min}$ (m³)		
$V_{1,max}$ (m³)	14 000	
$V_{2,max}$ (m³)		
T_{V1} (ºC)	3	
T_{V2} (ºC)	12	
$t_{duração}$ (h)	8	16

One of the purposes of the phase change material is to try to extend the decay of the volume V_1, instead of reaching the limit volume for V_1 at 18 hours, reach it as later as possible.

The quantity of energy storage in the tank is determined by Equation 3.

$$E = V \times \rho \times C_p \times (T_{top} - T_{base}) \tag{3}$$

Where T_{top} and T_{base} are the temperatures at the top and bottom of the tank, respectively.

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Table 3 – Energy stored in the tank.

Parameter	Value
V (m^3)	13 000
ρ (kg/m^3)	1 000
C$_p$ (J·kg^{-1}·K^{-1})	4 180
T$_{base}$ (ºC)	4
T$_{top}$ (ºC)	12
E (MJ)	434 720
E (MJ/m^3)	33.44

8. Results

Next, the results will be presented to the quantity of PCM necessary to store the desired energy value in each case. It will also be analyzed the impact of the PCM insertion into the water at 3 ºC over time. Finally it will also be presented the solidification and melting profile of the material during the charging and discharging process.

8.1. PCM volume

Knowing the energy to store and the latent heat of fusion, characteristic of the material, it is calculated the mass necessary of the PCM. From the density, we obtain the PCM volume.

$$m_{PCM} = \frac{E_{stored}}{\Delta H_{fusion}} \qquad (4)$$

$$V_{PCM} = \frac{m_{PCM}}{\rho_{PCM}} \qquad (5)$$

Applying Equation 4 and 5, the results are showed in Table 4.

Table 4 – Mass and volume of PCM for multiple energy storage.

10 %	
E (MJ)	43 472
m$_{PCM}$ (kg)	192 354
V (m^3)	250
20 %	
E (MJ)	86 994
m$_{PCM}$ (kg)	384 708
V (m^3)	499
30%	
E (MJ)	130 416
m$_{PCM}$ (kg)	577 062
V (m^3)	749
50 %	
E (MJ)	217 360
m$_{PCM}$ (kg)	961 770
V (m^3)	1 247

In the Figure 4, we can see the aspect of the tank with the multiple spheres inside a container.
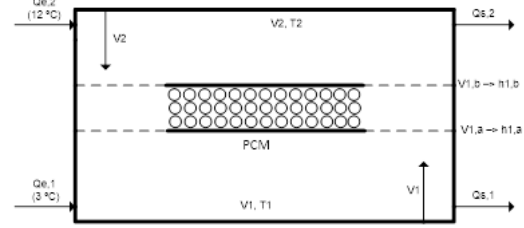

Figure 4 – Schematic diagram of the tank with PCM.

Through Figure 4, we can see that the heat transfer rate and also that the solidification mechanism will be different throughout the tank, as shown in Equations 6.

$$\begin{cases} UA = 0 \ if \ h_1 < h_{1,a} & (6.1) \\ UA = UA_{surface}\left(\frac{h_1 - h_{1,a}}{h_{1,b} - h_{1,a}}\right) \ if \ h_{1,a} \leq h_1 \leq h_{1,b} & (6.2) \\ UA = UA_{surface} \ if \ h_1 > h_{1,b} & (6.3) \end{cases}$$

The process of heat transfer only occurs when the water begins the contact with the base of the PCM. When the liquid water is below $h_{1,a}$ the UA parameter is zero. While the volume of liquid is between $h_{1,a}$ and $h_{1,b}$, the value off UA increases, depending on the fraction which is in contact with PCM. At last, when the water is above $h_{1,b}$ UA is maximum.

The variation of water in the tank is given by Equation 7.

$$\frac{d(V_1)}{dt} = Q_{e,1} - Q_{s,1} - \frac{Q_{transfer,1}}{C_p\rho(T_{V2} - T_{V1})} - \frac{Q_{transfer,2}}{C_p\rho(T_{V2} - T_{V1})} \qquad (7)$$

The term $\frac{Q_{transfer,1}}{C_p\rho(T_{V2}-T_{V1})}$ is the quantity of water that was in the volume V$_1$ and passed to volume V$_2$ while trading cold with the phase change material. Similarly, $\frac{Q_{transfer,2}}{C_p\rho(T_{V2}-T_{V1})}$ is the quantity of water that was in volume V$_2$ and passed to V$_1$, because the water received cold energy.

8.2. Number of spheres

To store the value of energy that are described at Table 4, we need to know how many spheres are need.

10 %		
V_{PCM} (m³)	D_{PCM} (m)	Spheres
250	1.00	477
	0.75	1 130
	0.50	3 812
	0.25	17 648
	0.20	59 561
	0.10	476 848
20 %		
V_{PCM} (m³)	D_{PCM} (m)	Spheres
499	1.00	953
	0.75	2 259
	0.50	7 624
	0.25	35 296
	0.20	119 121
	0.10	952 968
30%		
V_{PCM} (m³)	D_{PCM} (m)	Spheres
749	1.00	1 430
	0.75	3 389
	0.50	11 436
	0.25	52 943
	0.20	178 682
	0.10	1 429 452
50 %		
V_{PCM} (m³)	D_{PCM} (m)	Spheres
1 247	0.20	297 803
	0.10	2 382 420

Table 5 – Number of spheres with different diameters to store energy.

Simulations were performed for each amount of energy varying the spheres diameters, trying to find the optimal diameter for the desired goal. The desired goal is to find a diameter that can provide 1 000 m³ of cold water (V_1) after 18 hours (case without PCM, see Figure 3).

8.3. Results for 20 % storage
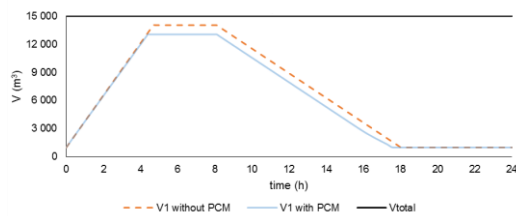
Figure 5 – V_1 variation for spheres with D = 1 m.
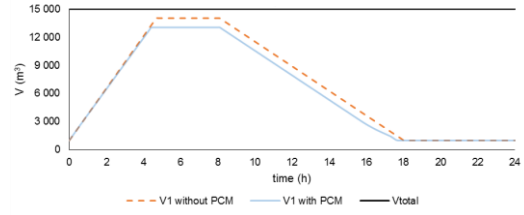
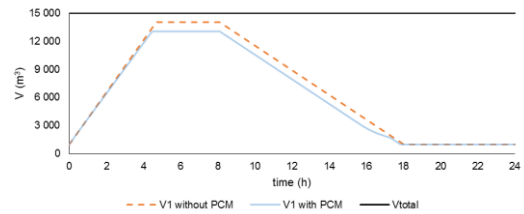*Figure 6 – V_1 variation for spheres with D = 0.75 m.*

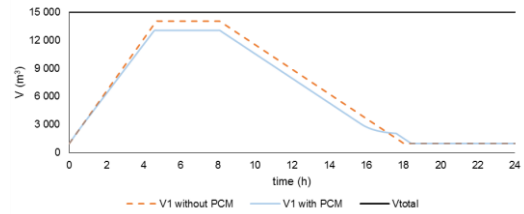*Figure 7 – V_1 variation for spheres with D = 0.50 m.*

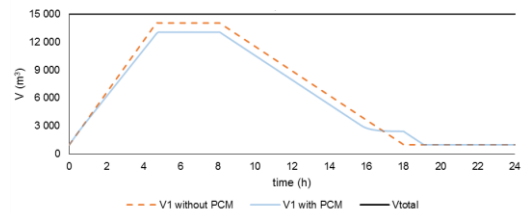*Figure 8 – V_1 variation for spheres with D = 0.25 m.*
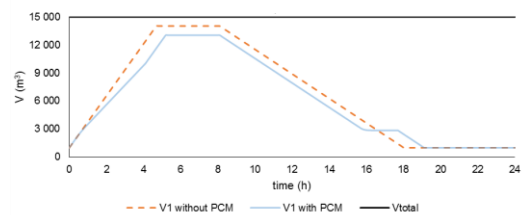
Figure 9 – V_1 variation for spheres with D = 0.20 m.

Figure 10 – V1 variation for spheres with D = 0.10 m.

In all figures (5 to 10), the maximum volume V1 with PCM is lower than the maximum volume V1 without PCM. This occurs, because the PCM occupies volume.

However, the minimum volume V_1 is always 1 000 m³, with or without PCM in the tank.

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Between Figure 5 and Figure 10, only the spheres with diameter of 25, 20 and 10 cm have positive results. Only those 3 diameters make the volume V_1 reach is minimum value in a time later than 18 hours, which is one of the objectives of this study.

On those three diameters, the 10 cm spheres are the ones that gives the best results, because are the ones that have more transfer area, which is a key parameter to the solidification and melting process.
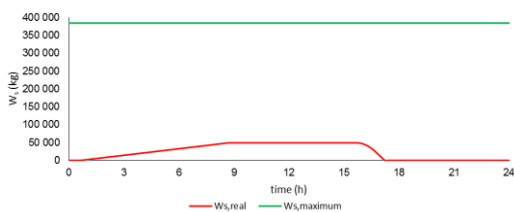

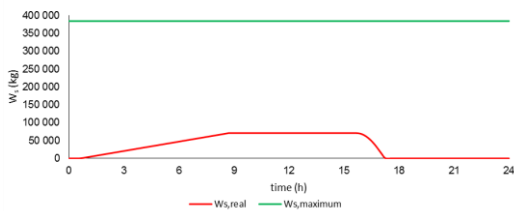*Figure 11 – Profile of solidification and melting of the PCM for spheres with D = 1 m.*

Figure 12 – Profile of solidification and melting of the PCM for spheres with D = 0.75 m.
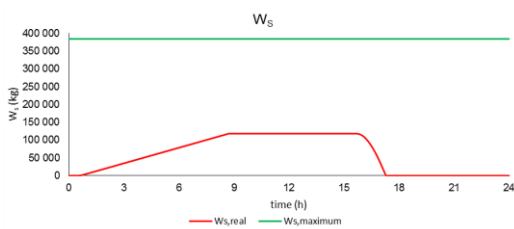

Figure 13 – Profile of solidification and melting of the PCM for spheres with D = 0.50 m.
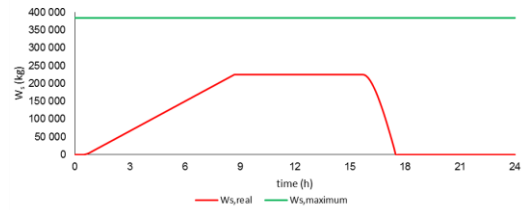

Figure 14 – Profile of solidification and melting of the PCM for spheres with D = 0.25 m.
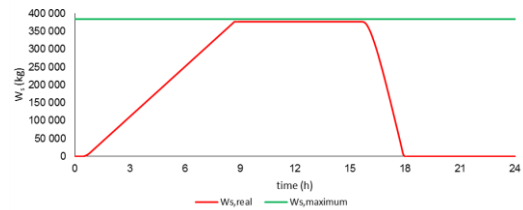

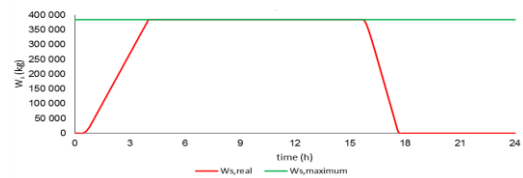*Figure 15 – Profile of solidification and melting of the PCM for spheres with D = 0.20 m.*

Figure 16 – Profile of solidification and melting of the PCM for spheres with D = 0.10 m.

For spheres with a diameter between 1 m and 50 cm, we can see that less than 1/3 of the PCM is used in the solidification process. That's the reason why the volume of cold water (V_1) contracts (see Figure 5*Figure 5*, Figure 6 and Figure 7), so the PCM with those diameters don't present positive results.

Although there are three favorable diameters, meeting the goal, only spheres with 10 cm solidify the entire fraction of the phase change material.

In all the diameters, the melting is way than the solidification, because the temperature gap in the charging process is 1 ºC instead of the 8 ºC gap for the discharge process.

Table 6 – Compilation of the results to store 20% of energy

D_{PCM} (m)	Number of Spheres	Total superficial Area (m²)	h (W·m⁻²·K⁻¹)	$W_{S,max}$ (kg)	$W_{S,real}$ (kg)	Δt (min)	Energetic gain (MJ)
1.00	953	2 294	128		49 385	-30	-
0.75	2 259	3 992	138		79 914	-24	-
0.50	7 624	5 988	153	384 708	118 187	-12	-
0.25	35 296	9 980	175		225 389	24	50 938
0.20	119 121	14 969	195		377 053	60	85 214
0.10	952 968	29 938	237		384 708	66	86 994

9. Conclusions

There are two types of systems for thermal energy storage: sensible and latent heat. This paper was developed for the latent heat system, and is operated using phase change materials. Although there are still problems with technology, in particularly with the phase separation and supercooling risk, for hydrate salts.

The energy storage in the phase change material chosen ($C_{14}H_{30}$) gives an efficiency ratio of 2.73, this means that 1m³ of PCM can store 2.73 more energy than 1 m³ of water.

For diameters of 1, 0.75, 0.50 m was not verified any useful gain of water volume so that could be used in a period longed that the tank already provides with no PCM.

For diameters between 50 cm and 1 m, there is the reduction of cold water available in the tank since the introduction of the PCM occupies volume that could be for water. Since the efficiency ratio is near 3, if there is no freezing of at least 1/3, if there is no freezing, of at least 1/3 of the PCM, the introduction of the PCM corresponds into a reduction of the calorific capacity of the tank in is all.

Although for 25, 20 and 10 cm, no matter the energy stored, these diameters showed gains of volume beyond 18 hours, which was the goal. But only the 10 cm diameter spheres made the solidification and melting of the PCM entirely.

These simulations were all made with an H/D ratio of 10 ratio of the container. These ratio had negative results for the discharge process for the storage of 50 % of energy. For the same amount of energy, but with an H/D ratio of 5, there were no problems with the simulation.

10. Acknowledgements

11. References

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