SEWAGE TREATMENT DEGRADATION THERMAL ENERGY MANAGEMENT SYSTEM OF SEWAGE TREATMENT PLANT

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Abstract: Objective: The paper is to study the sewage treatment degradation thermal energy management system of a sewage treatment plant, to achieve the energy saving and emission reduction. Methods: This paper studies the electron equivalent reaction of biochemical reaction (BR) of organic matter. Under the environmental conditions of biochemical degradation of sewage, BOD5 (Biochemical Oxygen Demand) is used to indicate the amount of heat generated by the degradation of organic matter in sewage. The paper designs a management system based on sewage heat recovery, and uses it to carry out heat recovery of sewage. Also, the energy-saving benefits produced by the heat management system are studied. Results: The sewage heat recovery system is more energy-efficient than the common air-conditioning supply system. In the use of sewage heat management system for one year, it achieves energy saving of 30.4% better than that of ordinary air-conditioning systems. The system for one year saves electric energy of 2145464kW.h, which is equivalent to saving 2511994×10^4 kJ primary energy. And this system saves 858.2 tons/year of standard coal, reduces CO_2 emissions by 2789.1 tons/year, reduces SO_2 emissions by 19.61 tons/year, reduces NO_2 emissions by 7.12 tons/year, reduces ash emissions by 135.19 tons/year, and saves tap water replenishment 40243 tons/year. Conclusion: The sewage thermal energy management system can utilize the thermal energy in the sewage, thereby using the sewage as a new clean energy. It can effectively improve China's current energy shortage and make a substantial contribution to China's energy saving and emission reduction goals.

Key words: *Energy; Sewage treatment; Thermal energy management; Energy saving and emission reduction*

1. Introduction

With economic and social development, China's environmental problems have become increasingly important. Due to people's pursuit of the economy, environmental problems have been ignored. Therefore, in recent years, China has studied and implemented a series of environmental protection measures. Water resources are an important part of environmental problems. A large amount of waste water has seriously polluted the drinking water and domestic water of people [1]. China's total wastewater discharge in 2014 reached 53.581billion cubic meters, and this number continues to grow at an extremely rapid rate. As a result, China ’s water shortage will worsen in the near future. Therefore, the reuse of wastewater will become the future development and research trend. And it will become one of the important development strategies in China [2]. The recovery and reuse of urban sewage can effectively solve the problem of urban domestic water supply, and reduce the discharge of urban sewage and the city’s demand for water resources. As the problem of sewage discharge is becoming increasingly serious, the reuse of sewage has become an object of scramble for research by worldwide scholars and relevant personnel in the industry. The use of recycled water has also become an important direction for scholars to open up new paths [3]. Also, the heat recovery in sewage naturally attracts the attention and research of many scholars. There is more heat in China’s urban sewage and microbial degradation, with a large space for utilization. The use of thermal energy in sewage can make sewage a new type of clean energy. It will not increase environmental pollution and will use environmental burden components as energy substances, greatly reducing the degree of pollution, to achieve the goal of energy saving and emission reduction [4, 5].

Urban sewage has not been effectively developed at present, thus, the reuse of thermal energy in urban sewage will become an important direction for future research. For example, the thermal energy in urban sewage is recovered to provide air-conditioning systems for buildings, thereby turning pollutants into new energy sources. Regarding the research and development of using the heat pump to recover the surplus energy in sewage, Japan was one of the earliest countries, and the heat pump system was put into practical use. Japanese research found that heat pump systems can save a quarter of initial investment and about half of the operating costs [6]. Urban sewage contains many pollutants and energy substances, and these substances have not been used very effectively. Therefore, some scholars have researched the heat in urban sewage, to understand the energy value that may be applied in urban sewage [7]. In a Swedish study, thermal energy from sewage was used to heat buildings. Studies have found that the use of heat pump systems for heating will be about 25% lower than the operating costs of boiler heating systems [8].

This paper studies the electron equivalent reaction of BR of organic matter. Under the environmental conditions of biochemical degradation of sewage, BOD5 is used to indicate the amount of heat generated by the degradation of organic matter in sewage. The paper designs a management system based on sewage heat recovery, and uses the system to carry out heat recovery of sewage. Also, the energy-saving benefits that the heat management system can produce are studied. This method can effectively improve China’s current energy shortage and make a substantial contribution to China’s energy saving and emission reduction goals.

2. Methodology

2.1. Electron equivalent generated by degradation in sewage

Calculating the electron equivalent generated by the degradation in sewage requires the combination of three half reactions, including the electron donor, the electron acceptor, and the cell synthesis [9]. As shown in Fig. 1, the BR consists of the addition of two reactions. That is, one of the two equations involved in the BR belongs to the functional equation and the other belongs to the cell synthesis equation.

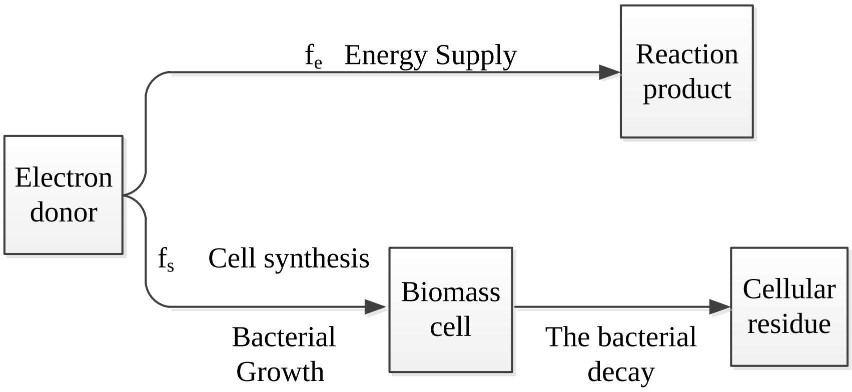

Figure 1: Energy utilization of BR electron donor

It can be obtained from the BR process that the electron donor in the figure participates in all energy supply reactions and cell synthesis reactions. In Figure 1, fs is the part where the electron donor is used for cell synthesis, and fe is the part where the electron donor is used for energy supply. And there is Eq. (1).

$$f_s + f_e = 1 \tag{1}$$

The process of bacterial reaction can be expressed by the change of reaction energy, and the equation describing the half-reaction of the electron donor is also used to describe the energy flow and cell synthesis during the bacterial reaction. Donor reaction energy (ΔGr) is the Gibbs reaction free energy generated by the combination of an electron donor and an electron acceptor. The electron donor half-reaction equation is combined with the cell synthesis half-reaction equation. The generated cell biomass and absorbed Gibbs free energy are called biomass synthesis energy (ΔGs) [10]. The total reaction equation of the BR is the sum of the functional response of the electron donor and the cell synthesis reaction in a certain proportion. The ratio of the two will depend on the energy transfer efficiency (ε) as well as the electron donor equivalent (A) required by electron donor reaction energy and to synthesize 1 equivalent of cytoplasmic energy [11]. The relationship between energy reaction and cell synthesis reaction is shown in Eq. (2) and Eq. (3).

$$\varepsilon \cdot A \cdot \Delta Gr + \Delta Gs = 0 \tag{2}$$

$$A = \frac{-\Delta Gs}{\varepsilon \cdot \Delta Gr} \tag{3}$$

Measurements have found that the energy transfer efficiency of aerobic heterotrophic bacteria is in the range of 0.2 to 0.4. The energy transfer efficiency for normal growth of autotrophic bacteria is usually in the range of 0.5 to 0.6. The energy transfer efficiency of normal growth of anaerobic bacteria is usually in the range of 0.45 to 0.65 [13].

2.2. Calculation of entropy increase in BR of organic matter

Water quality and quantity are the two main factors affecting the amount of heat contained in urban sewage. The main reasons affecting the water quantity are the water intake of the water supply plant and the drainage of the sewage plant. The main factors affecting water quality are the discharge of pollutants and the degree of purification of pollutants. In urban sewage, the heat increase due to degradation can be calculated by Eq. (4).

$$\Delta S_w = \Delta S_1 + \Delta S_2 \tag{4}$$

Where: ΔS_w represents the value of heat increase in urban sewage and the unit is J/K. ΔS_1 is the value of heat increase caused by various impurities in water and the unit J/K. ΔS_2 is the value of heat increase caused by the amount of sewage in the overall water environment and the unit is J/K. Therefore, to calculate the value of heat increase caused by impurities in the water, it is only necessary to obtain the heat value caused by the amount of sewage in the water and the total heat value generated in the water.

2.3. Organic BR electron equivalent

The energy required for the growth and reproduction of organisms is the energy obtained through redox reactions in organic matters and the radiant energy generated by sunlight [12].

Organic matters and oxygen are necessary substances that participate in the redox reaction that occurs in water. Organic matter in such a redox reaction exists as an electron donor, and oxygen exists as an electron acceptor. The general chemical equation of biological cytoplasm produced by BR in the water environment is recognized as $C_5H_7O_2N$. However, since the number and types of microorganisms in domestic sewage from different cities are not completely the same, the redox reactions are not exactly the same. The energy transfer produced in the redox reaction is even more difficult to measure, which has led to the inability to conduct large-scale studies of urban sewage. Therefore, the research and monitoring of such redox reactions are mainly accomplished by detecting the number of cells produced, that is, the cell yield coefficient ($Y_{C/C}$). The cell yield coefficient is the ratio of the number of cells per mole that a mole donor can produce. It can describe redox reactions in sewage, but the term $Y_{C/C}$ is only used for heterotrophic biological reactions. The autotrophic reaction is usually expressed as the ratio of carbon per mole cell to electron donor per mole ($Y_{C/M}$).

The oxides required for the redox reaction and the eventually produced substances can effectively calculate the degree of reduction of the redox reaction. The main products during the degradation of organic matter and biomass are CO_2, H_2O, NH_3, P_2O_5. Therefore, the reduction degree γ_d和γ_x of each carbon atom can be calculated by using Eq. (5).

$$\gamma = \frac{4n_C + n_H + 5n_P - 2n_O - 3n_N}{n_C} \quad (5)$$

Where: n_C, n_H, n_P, n_O, and n_N represents the number of corresponding atoms in the molecular formula of organic matter. The above calculation method of the degree of reduction per unit carbon atom is only applicable to the molecular formula of non-ionic organic matter. If the molecular formula of the organic matter is an ionic state, the degree of reduction per unit carbon atom is equal to the amount of charge provided during the reaction of the organic matter per mole divided by the number of carbon atoms.

The enthalpy change of the combustion reaction of microbial biomass is calculated as Eq. (6).

$$\Delta_r H = -115\gamma_i^o \quad (6)$$

Where: $\Delta_r H$ represents the standard molar heat of combustion (kJ/mol) of the biomass, and γ_i^o represents the degree of reduction.

The calculation method of the degree of reduction is related to the reactants and products of the chemical reaction. When the biomass combusts heat, the main products are CO_2, H_2O, N_2, and P_2O_5. Thus, at this time, the calculation for the degree of reduction is shown as Eq. (7).

$$\gamma_i^o = 4n_C + n_H + 5n_P - 2n_O \quad (7)$$

Therefore, the total BR equation of the degradation process of organic matter is expressed as Eq. (8).

$$0.083C_4H_4O_5^- + 0.125O_2 + 0.025NH_4^+ \rightarrow \\ 0.058H_2O + 0.067CO_2 + 0.142HCO_3^- + 0.025C_5H_7O_2N \quad (8)$$

2.4. Design of thermal energy management system

Sewage source heat pump system uses sewage as a cold and heat source for energy extraction and storage. As shown in Fig. 2, in the winter cycle heat exchange, the circulating working medium compressor of the sewage working system is compressed and enters the working medium at high-temperature and high-pressure hot steam. The heat that flows through the heat exchanger 1 and the circulating water heat exchanger provides hot water for heating at about 45 °C. At the same time, the hot steam condenses into a liquid, and the pressure reducing throttle expansion valve is converted into a low temperature and low-pressure liquid. The temperature of the working medium is lower than the temperature of the sewage. After the heat exchanger 2 and the sewage heat exchange well absorb heat from the water, it is evaporated into a low-temperature and low-pressure gas working medium, which is sucked into the compressor for compression. On this basis, the working medium carries out the next working cycle. Through such a cyclic process, the working system can convert the lower thermal energy in the sewage into high-grade thermal energy that can be directly used. In the summer cycle, the flow direction of the circulating working medium in the working system is completely opposite to that in winter through the reversing effect of the four-way valve and the check valve. Therefore, the heat exchanger 2 is a condenser, and the heat exchanger 1 is an evaporator. The working medium undergoes a similar cyclic process in winter, absorbing the heat in the room, and releasing it into the sewage to achieve the purpose of cooling.

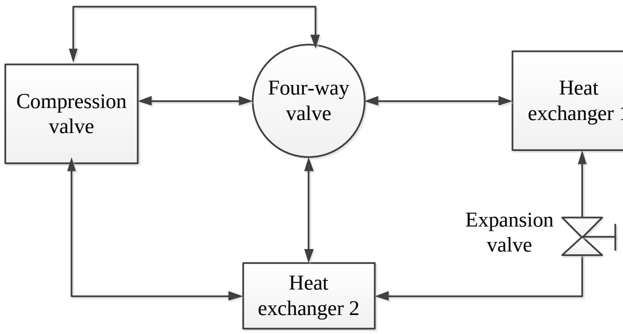

Figure 2: Simple water source heat pump system

Sewage source heat pump systems where sewage enters the heat pump unit directly are called direct systems, while the opposite is called indirect systems. The direct system has higher requirements on the water quality of the water-source water as well as the adaptability of the evaporator and the condenser. Since the evaporator and condenser need to have strong anti-pollution and anti-blocking capabilities, this paper uses an indirect system. Indirect systems replace evaporators and condensers with water-source water heat exchangers to provide heat, thus, indirect systems have relatively low requirements for water quality. From the current practice, even the urban primary sewage with extremely poor water quality and no treatment at all, as long as the anti-blocking technology of rotary backwashing is used, the entire system can continuously and safely take heat and cold for a long time.

Sewage source heat pump heating system can achieve 350% to 450% electricity conversion rate throughout the winter. When the thermal efficiency of power generation is 33%, the overall conversion efficiency of the sewage source heat pump is 115% to 150%, which is much higher than the district boiler room central heating system. In summer, cooling power consumption can be reduced by 30 to 40%. The area of the machine room is only 1/3 to 1/2 of the coal-fired boiler room. There is no need to store coal and slag, with the prominent advantages. The air-conditioning system made by using the sewage source can meet the needs of two different seasons, hot and cold. Compared with ordinary boiler heating and central air-conditioning methods, air-conditioning systems made by sewage sources have significantly lower initial investment, higher efficiency, and smaller area. Also, it can save much non-renewable energy.

3. Results

3.1. Property analysis results of organic matter

Inspection of the sewage after the primary treatment reveals that the organic matter content in the sewage is significantly reduced. The molecular weight is significantly reduced and relatively easy to dissolve (generally less than 0.025μm). The study also finds that most of the organic matter in the sewage is acidic. Therefore, this study will mainly focus on the redox reaction of acidic organics and combine it with other data such as cell yield coefficient. In this paper, 14 kinds of common organics in sewage are selected as the substrate for aerobic biological culture. The relevant parameters are shown in Fig. 3.

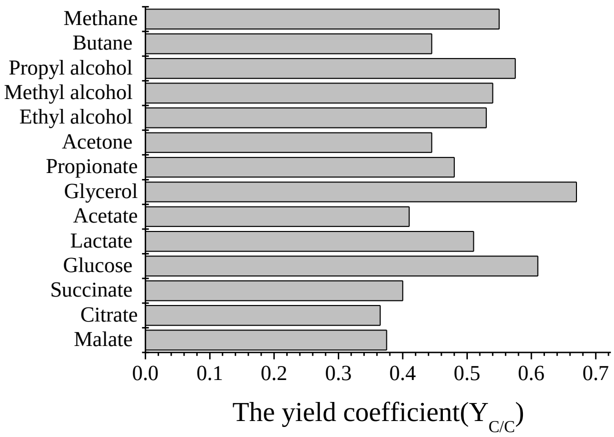

Figure 3: Yield coefficient of aerobic biological culture of organic substrate

3.2. Calculation results of thermal energy of BR of organic matter

The change of thermodynamic energy of malate ($C_4H_4O_5^{2-}$) is calculated during the BR. By calculation, fs=0.50 for malate can be obtained. Using the consumption of BOD to calculate the change of thermodynamic energy during the BR, it is obtained that the change of the thermodynamic energy of the formate BR is -13.45kJ/g BOD. According to the same method, the thermodynamic parameters of the BR process of all fourteen organic matters are obtained, as shown in Fig. 4.

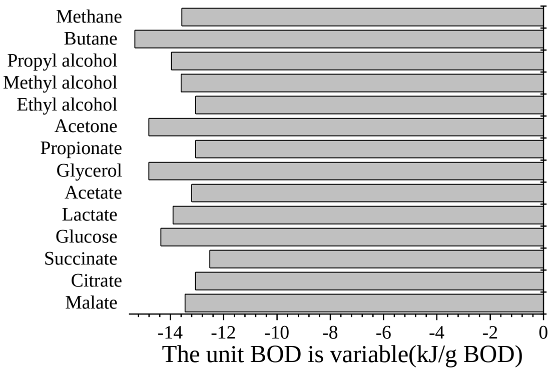

Figure 4: Thermodynamic parameters of the BR process

The enthalpy change ΔH during the BR of organic matter is shown in Figure 5. BOD and the enthalpy change ΔH during the BR of organic matter have a linear correlation. It can be seen that during the biochemical degradation of organic matter in the water environment, ΔH has an increasing tendency with the increase of BOD.

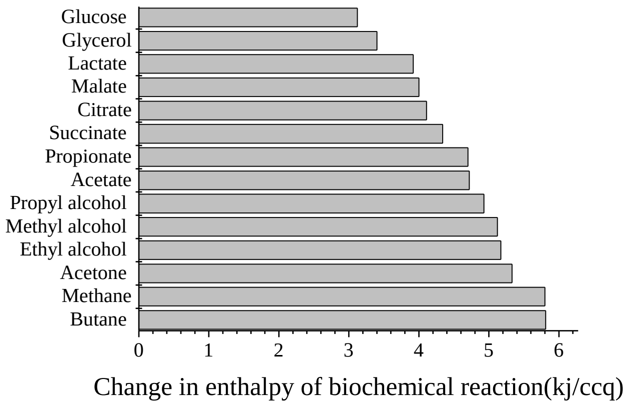

Figure 5: Enthalpy change ΔH during the BR of organic matter

3.3. Energy consumption of sewage source heat pump air-conditioning system

The energy supply system of conventional air conditioners consumes approximately 2.82 million kilograms of coal per year, equivalent to approximately 7.05 million kW per hour of electricity, and approximately 826×10^8kJ of primary energy. The sewage source heat pump air conditioning system consumes approximately 2 million kg of coal per year, equivalent to approximately 4.91 million kW per hour, and approximately 575×10^8kJ of primary energy. The annual operation saves 858186 kg of standard coal, 2.14 million kW of electricity per hour, and about 251×10^8 kJ of primary energy. The energy saving effect is significant. Compared with the conventional air conditioning system, the annual energy saving rate is 30.4%, as shown in Fig. 6.

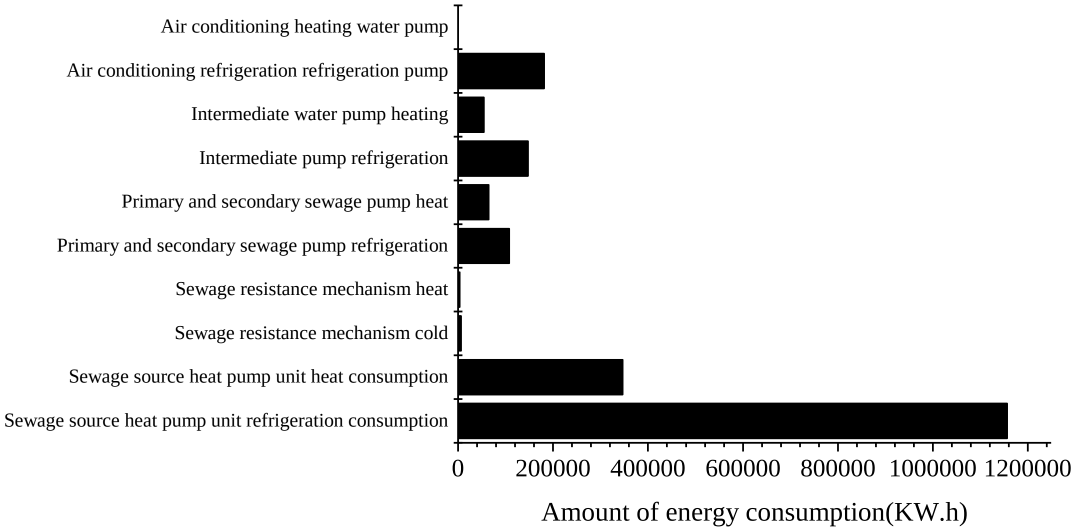

Figure 6: Power consumption of sewage source heat pump air conditioner

3.4. Water saving benefits

When the sewage is circulated in the air-conditioning system for refrigeration, the water savings are very large. Using sewage to circulate in the air conditioner to take away heat can eliminate many cooling water requirements. Therefore, the use of sewage as cooling water can greatly reduce the demand for cooling water and only a small amount of intermediate circulating water can be used. After calculation, the cooling water replenishment is considered at 2% of the circulating water volume, and the sewage source heat pump system can save 40243 tons of tap water throughout the year. At present, the energy consumption of tap water production in China is generally high. According to the current energy price, the energy consumption price of tap water per cubic meter is equivalent to about 7-8kW.h of electricity. Therefore, the tap water saved directly by the sewage source heat pump system is equivalent to saving 281701-321944kW.h of electricity. The energy-saving benefits produced by water saving are also very worthy of attention, which is equivalent to 13-15% of electricity directly saved by the sewage source heat pump system, greatly increasing the advantages of the system.

4. Discussion

The effective recovery and utilization of thermal energy in urban sewage is one of the effective measures to implement energy saving and environmental protection. And it is also one of the effective ways to achieve comprehensive utilization of sewage thermal energy. The recovery and utilization of the thermal energy in urban sewage can expand the benefits of urban sewage treatment and energy utilization, realizing another kind of recovery and reuse of wastewater. It also helps to achieve the national energy saving and emission reduction as well as circular economy goals, so that national development is in a stable, environmentally friendly and efficient state.

Due to the large amount of pollutants and heat in urban sewage, when it is discharged into other water flows, it will have a large impact on the overall water flow, resulting in an increase in heat. The amount of heat in the water reflects the recovery and utilization of sewage to a certain extent, which indicates that the thermodynamic impact of sewage on the water environment. Therefore, thermodynamic entropy can be used as a comprehensive index for quantitative assessment of water environment impact. The increase of entropy in urban sewage is mainly caused by two aspects of water quantity and water quality. The increase in entropy caused by water quantity is mainly due to the temperature difference. The increase in entropy caused by water quality is due to the main pollutant in sewage: organic matter, nitrogen and phosphorus. According to electron equivalent equations for BR in the water environment, the thermodynamic enthalpy changes during the BR of pollutants can be calculated. According to the laws of thermodynamics, the corresponding thermodynamic entropy calculation equations for the water environment during the biochemical degradation of pollutants can be obtained.

The main reason for the increase in heat in sewage is inorganic phosphorus, followed by organic matter, and the increase in heat caused by inorganic nitrogen is the smallest. This paper studies the heat of sewage and uses the heat recovery system of sewage to recover the heat in sewage, which shows that the sewage source heat pump system is feasible in the utilization of urban sewage. Because the equipment used in this study is not advanced enough, the annual measurement performed in this study is only measured at a fixed time point every day. But it has also achieved significant results. If real-time monitoring of the situation throughout the day can be performed, it will greatly increase the accuracy of the study.

5. Conclusion

Compared with the conventional air-conditioning system, the annual operation saves 2145464kW.h (the annual operation energy-saving rate is 30.4%). It is equivalent to a primary energy saving of 2511994×10^4kJ, a standard coal saving of 858.2 tons/year, a reduction in CO_2 emissions by 2789.1 tons/year, a reduction in SO_2 emissions by 19.61 tons/year, a reduction in NO_2 emissions by 7.12 tons/year, a reduction in ash emissions by 135.19 tons/year, and a tap water replenishment saving of 40243 tons/year.

The effective recovery and utilization of sewage can greatly reduce China's energy consumption. In China, air conditioning and heating systems consume much non-renewable energy every year. Therefore, the effective use of wastewater and sewage heat pump air conditioning systems will make sewage a new type of clean energy. It can reduce energy consumption and pollutant emissions, making a huge contribution to China's environmental protection.

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