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Bilge water treatment and desalination based on HDH technology: an experimental investigation of a demonstration plant

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ABSTRACT

Next to energy, water can be seen as the foundation for a livable world in the future. Therefore, we need water treatment systems for desalination as well as for treatment of brackish and industrial water. Within this work, a demonstration unit based on the humidification dehumidification process is presented. The test series include measurements with pure water and brine in various concentrations. The influence of the location of fluid injection into the humidifier as well as the influence of air injection will be discussed theoretically and based on the experimental data. It can be shown that saturation of air strongly depends on bubble size and that a combination of humidification in the bubble column and humidification above the fluid surface occurs. In the next step, the demonstration unit is investigated for bilge water, a mixture of water, heavy oil, and sediments, which occurs in the shipping industry and is so far burned in the cement industry. The goal of our process is the separation and recovery of the oil phase to use it, for example, as base material for recycling oil.

Keywords: HDH; Wastewater treatment; Desalination; Bilge water; Heat pump

1. Introduction

Secure, affordable, and resource efficient water supply will play a similarly important role for future societies as renewable energy supply. Desalination in arid regions is probably the most crucial application. However, industry tries to reduce the amount of water needed for a process as well and seeks for new ways to recycle their industrial wastewater within the company to reduce disposal costs and environmental damages.

These boundaries lead to necessary research and development of small, robust, low-cost, and flexible water treatment systems, which can cover the whole range of applications: brackish water treatment in remote areas, standalone desalination for isolated regions as well as industrial wastewater treatment in different process chains [1].

Common thermal-driven desalination technologies such as multieffect distillation (MED), multistage flash distillation (MSF), or thermal vapor compression are unsatisfactory for this purpose as they are only profitable in large scale. Although the efficiency can be increased by hybridization [2], the complexity is also increased. Reverse osmosis (RO) on the other hand could be used in small-scale applications as well. Therefore, especially in Southern Europe and North Africa, RO units are favored for desalination compared with MED and MSF [3]. However, the choice of an appropriate membrane strongly depends on the application. While research and development led to affordable and effective membranes for desalination, membranes for industrial wastewater are still very expensive, as each educt needs a different membrane.

Therefore, humidification dehumidification (HDH) technology gained research interest during the last decade.

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This technology aims to implement the natural water cycle in a technical process. As humidifier, spray towers with different fillings are state-of-the-art [4–6]. However, Narayan et al. [7,8] suggest a bubble column humidifier. Generally, the group of Lienhard at MIT carried out various work on HDH technology. They covered thermodynamic analysis [9] and optimization [10] as well as combination of HDH with RO [11]. Recently, Liu and Sharqawy [12] analyzed a bubble column humidifier and dehumidifier in one process. Multistage systems have also been investigated by some researchers [13,14]. Although the process is mostly discussed for solar-driven desalination and treatment of brackish water [15,16], it is also possible to use it for oil-containing fluids [17]. However, most of the analyses are theoretical or for laboratory-scale systems.

Therefore, the main questions that will be discussed within this study are

- How can HDH technology be built in an industrial manner and on demonstrator scale?
- How does liquid height in the bubble column humidifier influence the productivity of the system?
- Which similarities and differences occur for the two applications of desalination and wastewater treatment?

2. Fundamentals

HDH technology imitates the natural water cycle of the Earth (see Fig. 1). In the first step, air is heated up and humidified in direct contact with countercurrent water stream in the humidifier. Subsequently, the air stream enters the dehumidifier and cools down. The water condenses and can be discharged. The heat of condensation is used to preheat the seawater stream which is further heated (e.g., by solar energy) before entering the humidifier at the top. Mostly, spray towers or falling film humidifiers are used. Narayan [18] suggested bubble columns as humidifier and dehumidifier to increase heat and mass transfer. Hence, heat and mass transfer in general [19], condensation in presence of noncondensable gases [20], and experimental validation [21] have been carried out and patents have been granted [22–24].

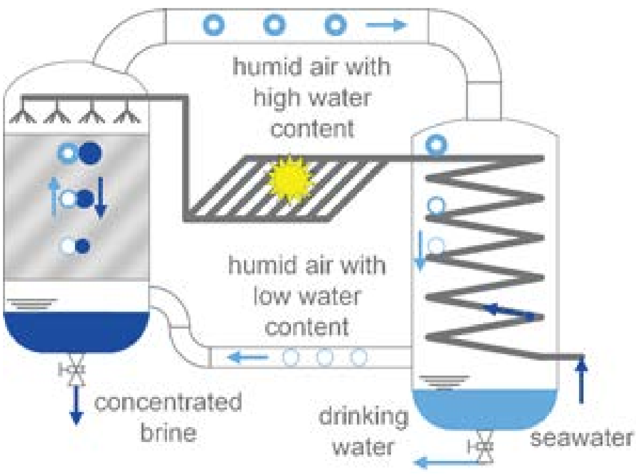

Fig. 1. HDH technology for desalination.

3. Experimental setup

Fig. 2 shows the setup of our system. It contains three different cycles: wastewater cycle, air cycle, and heat pump cycle. A bubble column with a base area of 1 m^2 and a liquid height of 1 m serves as a humidifier. Wastewater or seawater, respectively, can either be pumped into the humidifier at the bottom or sprayed from the nozzles on the top. Air entry is realized with nozzles at five different heights as well as on the surface. In that way, the setup ensures variable contact times between air and bilge water. This is important as longer contact times will lead to better heat and mass transfer but also to higher pressure drops. The lowest nozzle is about 20 cm above the bottom of the bubble column; the highest one is about 20 cm below the liquid height. Nozzles are preferred compared with sparger plates in the demonstration unit so that the bilge water cannot flow back into the air circuit. Dehumidification takes place in a plate heat exchanger. Energy supply is realized with a heat pump, which recovers the heat of condensation to heat the humidifier to about 60°C.

The demonstrator is designed for bilge water treatment within the shipping industry (see Fig. 3). Bilge water is a mixture of salt, water, and machine oil. So far, bilge water is treated in large centrifuges to get a mixture of 50% water and 50% oil. Afterwards, the mixture is burned in the

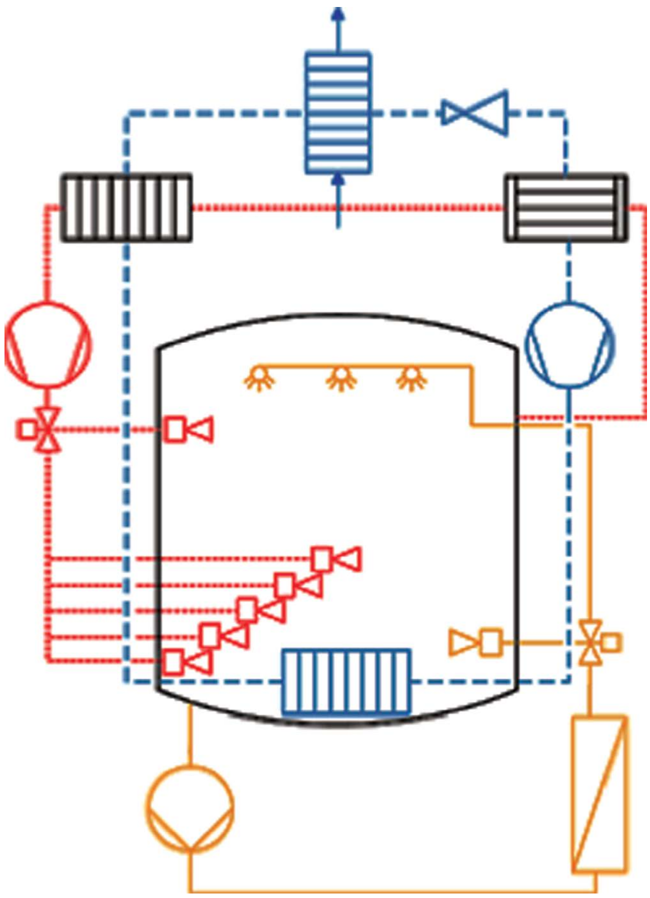

Fig. 2. Scheme of demonstration unit with heat pump cycle (dashed line, blue), air cycle (pointed line, red) and medium cycle (solid line, yellow).

Fig. 3. Bilge water treatment from the shipping industry.

cement industry. Our technology aims to concentrate the emulsion to increase the oil content to more than 95% and use it as recycling oil with economic value. As the concentration of oil has to be done discontinuously, the demonstrator is operated batchwise. Next to bilge water treatment, the system can also be operated continuously for desalination purpose. The demonstrator in the laboratory is displayed in Fig. 4. The dimensions are roughly a length of 3.5 m, a width of 1.5 m and a height of 2.5 m.

Fig. 4. Demonstration unit in the laboratory.

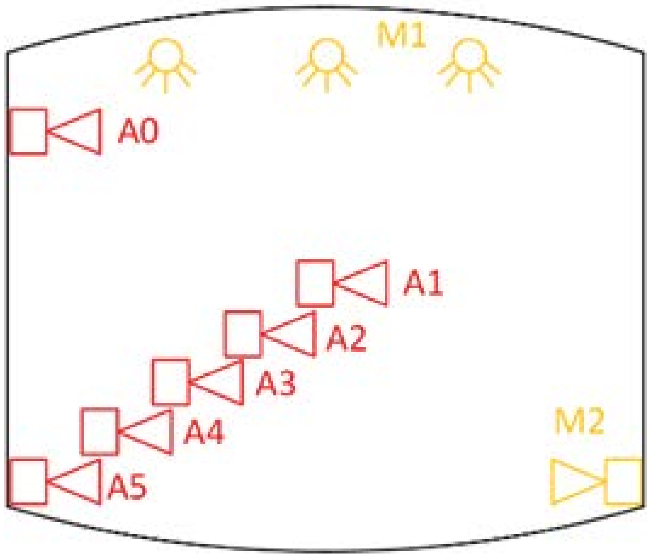

Fig. 5. Location and numbering of air nozzles (A) and medium nozzles (M).

4. Results and discussion

Results are discussed for desalination in Section 4.1, for bilge water treatment in Section 4.2. Nozzles for air entry are named with "A," nozzles for medium entry with "M." The nozzles are numbered according to Fig. 5.

4.1. Desalination

Firstly, the influence of air and medium entry into the humidifier is investigated. In Fig. 6 the productivity of the system is displayed for air entry through nozzle A1–A5 and for medium entry at the bottom (M1, striped bars). In theory, productivity should increase for increasing nozzle number as air from nozzle A5 has a higher retention time than air from nozzle A1. Therefore, the contact time between air bubbles and liquid is higher and so is the available time for saturation. This should lead to a higher specific water content (kg water per kg air) and higher productivity. However, it is obvious from Fig. 6 that productivity is almost constant for all nozzles. One possible explanation for this behavior is that even the retention time of air from nozzle A1 is long enough for full saturation. Therefore, a further test series with medium entry from the top is carried out (see Fig. 6, gray bars). It can be seen that the productivity of the system is almost doubled. Hence, the water content of the air is further increased above the surface. This means that the air from nozzles A1–A5 is not fully saturated at the surface of the bubble column.

The reason for this behavior is found by visual inspection of the inside of the humidifier. The bubbles are far bigger than expected (more than 10 cm in diameter). Therefore, the bubbles cannot be fully saturated, as mass transfer resistance is too high. Hence, the bubbles are just apparently saturated at the surface, break to smaller bubbles, and

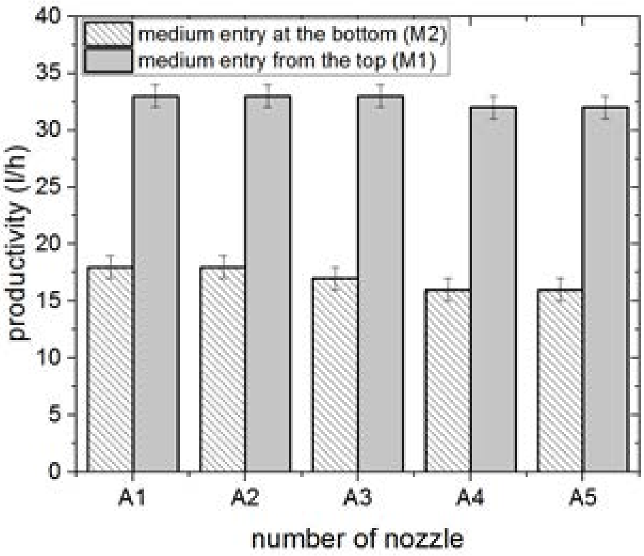

Fig. 6. Productivity for air entry in nozzle A1–A5 (striped: medium entry from bottom nozzle, gray: medium entry from top nozzle); salt concentration 0%.

are further saturated above the surface. Such a behavior is already known from cooling towers, which are operated with saltwater instead of pure water. Although the problem itself is the opposite (evaporation of water into air compared with humidification of air in water), the shell model of Sadafi et al. [25] is still comparable (see Fig. 7). For cooling towers, the saltwater droplet first adjusts its temperature so that the water and the surrounding air are in thermodynamic equilibrium. Afterwards, the water evaporates at constant temperature, which leads to a salt shell around the droplet. After the shell is closed, water first has to diffuse through the salt shell before it is evaporated. Therefore, the resistance of the salt shell slows down the dry out. Hence, the necessary amount of water in cooling towers is increased for operation with saltwater compared to pure water. Furthermore, the cooling tower height has to be increased to allow the time for appropriate levels of evaporation through the salt shell.

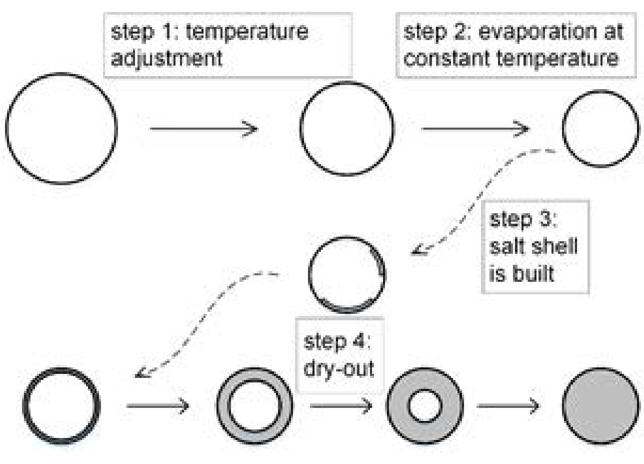

Fig. 7. The four steps of evaporation of saltwater in cooling towers according to Sadafi et al. [25].

The same mechanism may be found in the air bubbles, which are humidified in our process. In this case, the driving force (diffusion of water into the air bubble) is reduced as soon as the concentration of water in an outer shell of the air bubble increases (so the salt shell reported by Sadafi et al. [25] is a shell with high water concentration in our case). Therefore, the shell of the air bubble is saturated, whereas the core of the air bubble is not fully saturated. If the bubble breaks at the liquid surface, the unsaturated air in the core of the bubble can be saturated as well and the productivity is increased. Hence, a combination of bubble column humidifier with additional nozzles at the top is of interest for commercialization. Another solution is the reduction of bubble size within the humidifier. Further work should be carried out in this area as the knowledge gaps prevent appropriate design of industrial scale bubble column humidifiers. Especially the bubble behavior in agitated systems strongly depends on the liquid within the process. Generally, one would assume that bubbles form, mix, and break again. However, in our case due to the high viscosity of the bilge water, the bubbles seemed to grow until the surface of the bubble column. Note that the spherical model is just a schematic approximation to show the theory of a shell. In reality, bubbles formed in the bubble column do not have an ideal spherical shape.

Subsequently, the influence of salt concentration is investigated in Fig. 8. The increase of productivity for medium entry from the top compared with medium entry at the bottom can be seen for all three salt concentrations. Furthermore, a slight decrease in productivity for increasing salt concentration occurs. This can be explained qualitatively based on thermodynamics. The higher the salt concentration is, the lower is the humidity of air. For example, the humidity of air above a saturated salt solution at 25°C is just 75.5% [26].

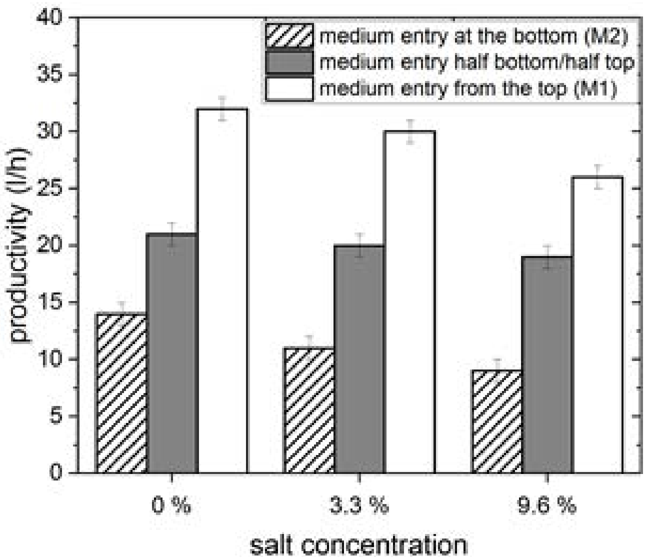

Fig. 8. Productivity for different salt concentrations with air entry from top (left: medium entry from bottom, middle: medium entry from top and bottom, right: medium entry from top).

Hence, the absolute water content which is proportional to the productivity of the system decreases with increasing salt concentration.

4.2. Wastewater treatment

Before testing bilge water in the demonstration unit (Fig. 4), it is preliminary analyzed with different analytic devices. First, water content is measured by means of Karl Fischer titration. The results give a value of about 44.6% of water within the water/oil/salt-emulsion, salt concentration is less than 1%. Second, elementary analysis based on CHNS and inductively coupled plasma atomic emission spectroscopy (ICP-AES) method is carried out. CHNS gives 31.05% carbon (C), 10.32% hydrogen (H), 0.24% nitrogen (N), and 0.27% sulfur (S). ICP-AES results reveal mainly aluminum, calcium, iron, phosphor, and sulfur, whereas the sulfur content is measured to 0.95%. As ICP-AES is more reliable than CHNS for fractions lower than 1%, sulfur content of 0.95% is more realistic than 0.27% from CHNS method. Last, gas chromatography is applied to identify hydrocarbon structures in the bilge water (Fig. 9). It is obvious that bilge water mainly consists of linear alkanes with about 9–32 carbon atoms with a plateau between 14 and 31 in which concentration is more than 4%. In a combined gas chromatography mass spectroscopy analysis, we identified more than 120 different chemical compounds in the bilge water.

Subsequently, bilge water is preliminary heated to separate the water phase from the organic phase. Fig. 10 shows both phases in the bilge water (middle). The goal of the project is to reach a pure oil phase as it is shown on the left hand side in Fig. 10 and reached after the heating process. This would lead to a pure water phase as well (right hand side of Fig. 10 shows tab water to illustrate the difference). The main problem that occurred during the preliminary tests of the bilge water is its extremely high viscosity. This is a main issue for filling bilge water into the demonstration unit and draining it after water and oil are separated. Furthermore, the high viscosity of bilge water and oil phase will lead to higher bubble diameter and, therefore, to lower mass transport. Therefore, the time needed for the separation will be longer than for desalination [27–29]. First measurements in the demonstration unit prove some of the theoretical aspects mentioned so far. Generally, the process works for bilge water similar as for saltwater. When we use a mixture of about 330 L of tab water and 190 L of bilge water into the demonstration unit, the process gains a productivity of 22 L/h for a medium entry at the top (M1) and 7 L/h for medium entry at the bottom (Fig. 11). If we compare Figs. 6 and 11, the deterioration in productivity from saltwater to the bilge water/water–mixture is obvious. However, next to the quantitative drop in productivity, the qualitative behavior of an apparent saturation also occurs in the new experiments. Fig. 12 gives evidence as we observe again an almost linear behavior between the productivity and the share of medium entry on top (M1).

Fig. 10. Pure oil (left), bilge water including oil and water phase (middle) and pure tab water (right).

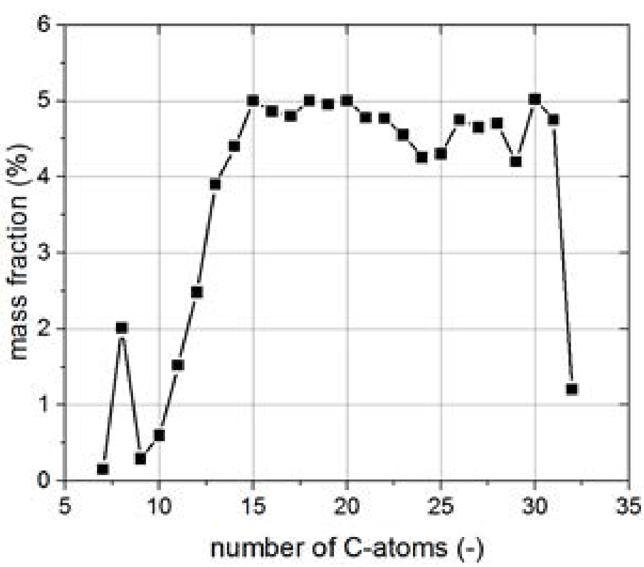

Fig. 9. Analysis of bilge water by means of gas chromatography.

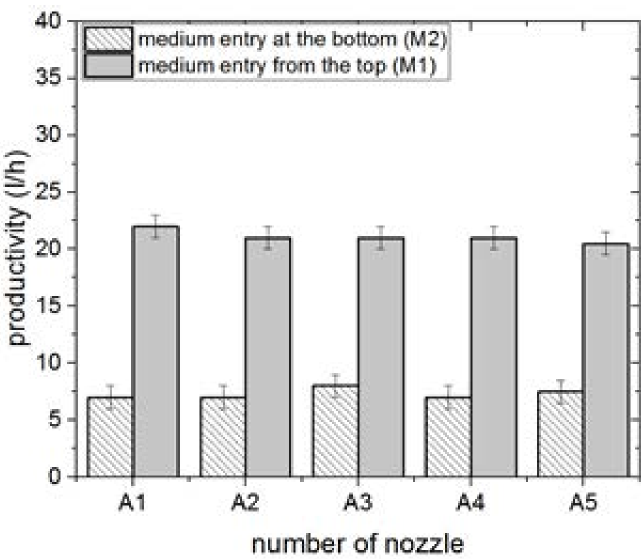

Fig. 11. Productivity for air entry in nozzle A1–A5 (striped: medium entry from bottom nozzle, gray: medium entry from top nozzle); mixture of 330 L of tab water and 190 L of bilge water.

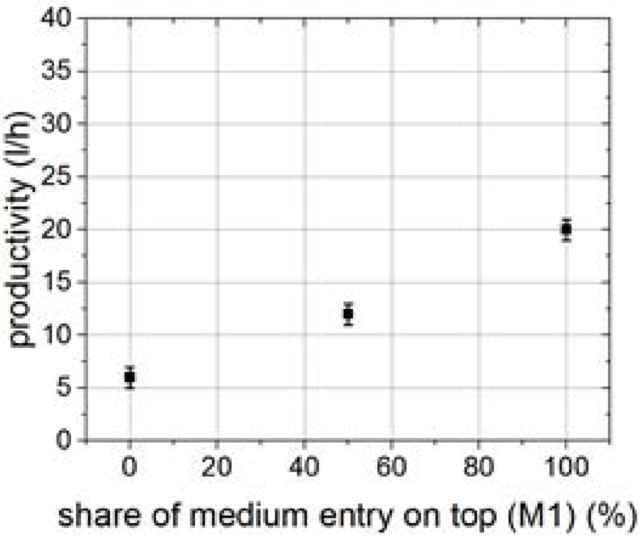

Fig. 12. Productivity depending on share of medium entry on top (M1); mixture of 330 L of tab water and 190 L of bilge water.

5. Conclusion

Desalination, brackish water treatment as well as wastewater treatment in industries play a key role for future societies in terms of social, economic, and environmental aspects. Therefore, we need to develop small-scale and robust systems for decentral (waste) water treatment. This paper suggests to apply HDH technology combined with a heat pump for desalination and treatment of bilge water. The main results are

- HDH technology can be built in an industrial manner; however, lack of fundamental research on humidification of air in bubble columns complicates an appropriate design of components.
- Liquid height within the humidifier does not influence the productivity, as mass transfer resistance is too high for full saturation. Therefore, demonstration units should combine bubble column humidifier with spray nozzles.
- As the physical background of concentrating bilge water is similar to desalination, it is generally possible to use the unit for both applications.
- However, due to the difference in physicochemical properties, such as viscosity, the productivity drops significantly for bilge water compared with saltwater.

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