15th International Conference on Environmental Science and Technology

Rhodes, Greece, 31 August to 2 September 2017

Experimental Analysis of a Demonstration Plant for Bilge Water Treatment and Desalination Based on Humidification Dehumidification Technology

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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 includes 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 a next step, the demonstration unit is investigated for bilge water, a mixture of water, heavy oil and sediments which occur 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, waste water 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 waste water within the company to reduce disposal costs. 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, stand-alone desalination for isolated regions as well as industrial waste water treatment in different process chains. Common thermal driven desalination technologies like multi-effect distillation (MED), multi-stage flash distillation (MSF) or thermal vapor compression (TVC) are unsatisfactory for this purpose as they are only profitable in large-scale. Reverse osmosis (RO) on the other hand could be used in small-scale applications as well. However, the choice of an appropriate membrane strongly depends on the applications. While research and development led to affordable and effective membranes for desalination, membranes for industrial waste water are still very expensive as each educt needs a different membrane. Therefore, humidification dehumidification (HDH) technology gained interest in research during the last decade. Various work has been carried out by the group of Lienhard at MIT. They covered thermodynamic analysis (Narayan *et al.* 2012b) and optimization (Narayan *et al.* 2013a) as well as combination of HDH with RO (Narayan *et al.* 2012a). Multi-stage systems have also been investigated by some researcher (Chehayeb *et al.* 2015; Kang *et al.* 2015). However, analyses are mostly theoretical or for lab-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 productivity of the system?
- Which similarities and differences occur for the two applications of desalination and waste water treatment?

2. Fundamentals

HDH technology imitates the natural water cycle of the earth (see ***Figure 1***). In a 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 sea water 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 (Narayan 2012) suggested bubble columns as humidifier and dehumidifier to increase heat and mass transfer. Hence, heat and mass transfer in general (Narayan *et al.* 2010), condensation in presence of non-condensable gases (Thiel, Lienhard 2012) and experimental validation (Tow, Lienhard 2014) has been carried out and patents have been granted (Narayan *et al.* 2013b; Narayan *et al.* 2013c).

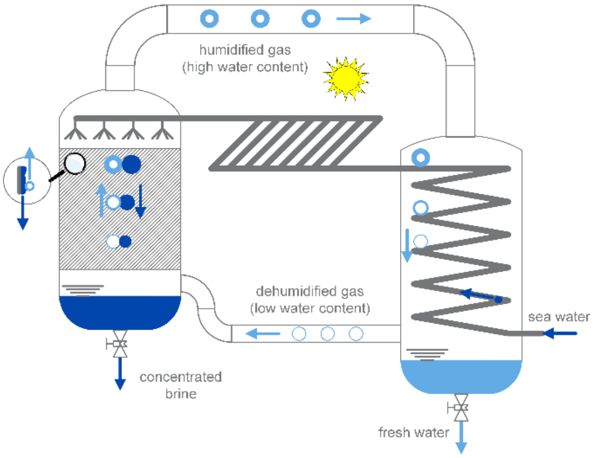

Figure 1: HDH-technology for desalination

3. Experimental setup

Figure 2 shows the setup of our system. It contains of three different cycles: waste water cycle, air cycle, and heat pump cycle. A bubble column with an area of 1 m² and a height of 1 m serves as a humidifier. Waste water can either be pumped into the humidifier at the bottom or sprayed from the nozzles on the top. Air entry is realized at five different heights as well as on the surface. 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 ***Figure 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 cement industry. Our technology aims to further 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 batch-wise. Next to bilge water treatment, the system can also be operated continuously for desalination purpose. The demonstrator in the lab is displayed in ***Figure 4***. The dimensions are roughly a length of 3.5 m, a width of 1.5 m and a height of 2.5 m.

4. Results and Discussion

Results are discussed for desalination in subchapter 4.1, for bilge water treatment in subchapter 4.2. Nozzles for air entry are named with “A”, nozzles for medium entry with “M”. The nozzles are numbered according to Figure 5.

4.1. Desalination

Firstly, the influence of air and medium entry into the humidifier is investigated. In ***Figure 6*** the productivity of the system is displayed for air entry through nozzle A1 to 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

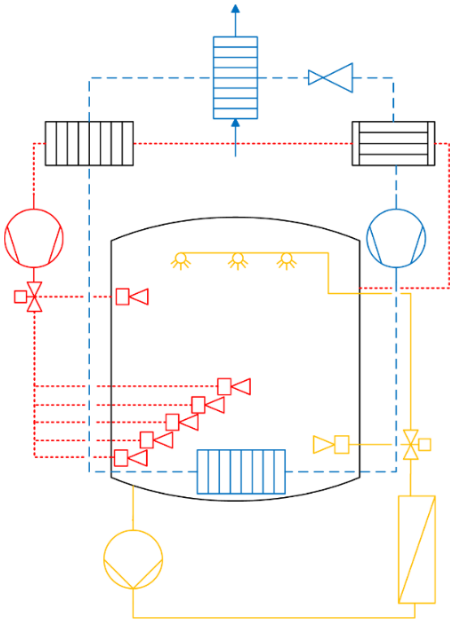

Figure 2: Scheme of demonstration unit with heat pump cycle (dashed line, blue), air cycle (pointed line, red) and medium cycle (solid line, yellow)

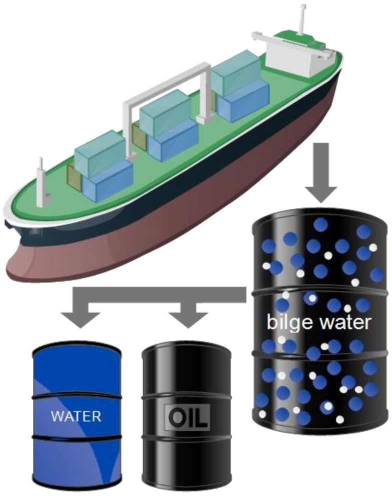

Figure 3: Bilge water treatment from the shipping industry

Figure 4: Demonstration unit in the lab

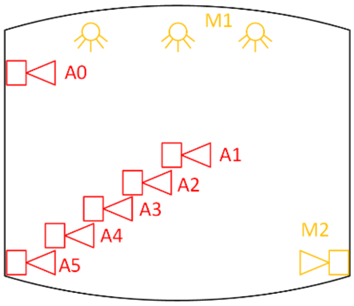

Figure 5: Location and numbering of air nozzles (A) and medium nozzles (M)

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 Figure 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 ***Figure 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 to 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) and cannot be fully saturated as mass transfer resistance is too high. Therefore, the bubbles are just apparently saturated at the surface, break to smaller bubbles and are further saturated above the surface. Hence, a combination of bubble column humidifier with additional nozzles at the top is of interest for commercialization. Another solution is reducing the 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.

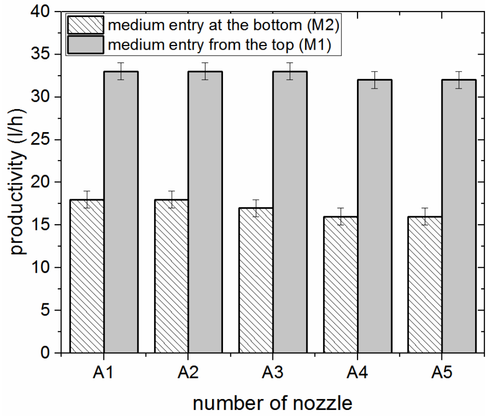

Figure 6: Productivity for air entry in nozzle A1 to A5 (striped: medium entry from bottom nozzle, gray: medium entry from top nozzle); salt concentration 0 %

Subsequently, the influence of salt concentration is investigated in ***Figure 7***. The increase of productivity for medium entry from the top compared to 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 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 %. Hence, the absolute water content which is proportional to the productivity of the system decreases with increasing salt concentration.

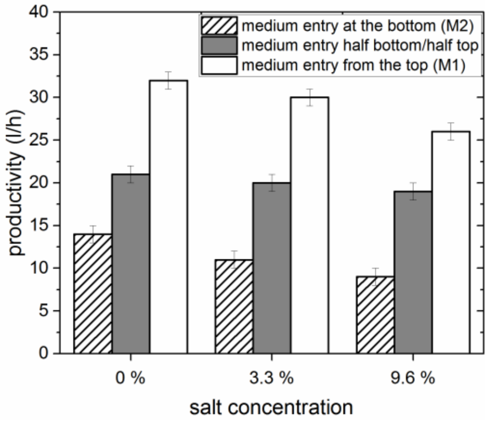

Figure 7: Productivity for different salt concentrations with air entry from top (left: medium entry from bottom, middle: medium entry from top and bottom, right: medium entry from top)

4.2. Waste water treatment

Before testing bilge water in the demonstration unit (***Figure 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. Second, elementary analysis based on CHNS and 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 (***Figure 8****)* It is obvious that bilge water mainly consists of linear alkanes with about 9 to 32 carbon atoms with a plateau between 14 and 31 in which concentration is more than 4 %. In a combined gas chromatography mass spectroscopy (GC-MS) 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. ***Figure 9*** 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 ***Figure 9*** and reached after the heating process. This would lead to a pure water phase as well (right hand side of ***Figure 9*** 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

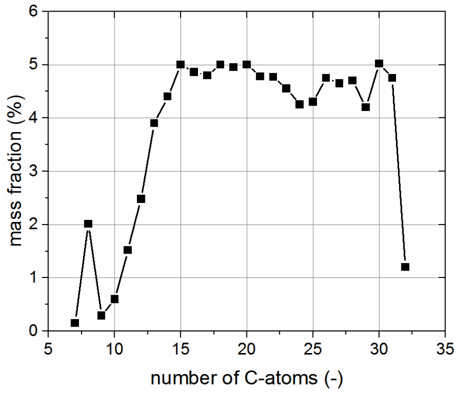

Figure 8: Analysis of bilge water by means of gas chromatography

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 (Kantarci *et al*. 2005; Li, Prakash 1997; Schäfer 2005). 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 salt water. 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 (***Figure 10***). If we compare ***Figure 6*** and ***Figure 10***, the deterioration in productivity from salt water 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. ***Figure 11*** gives evidence as we observe again an almost linear behavior between the productivity and the share of medium entry on top (M1).

Figure 9: Pure oil (left), bilge water including oil and water phase (middle) and pure tab water (right)

5. Conclusion

Secure and affordable water supply will play a key role for future societies. Therefore, we need to develop small-scale and robust systems for decentral (waste) water treatment. This paper suggests to apply humidification dehumidification 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 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 the one of desalination, it is generally possible to use the unit for both applications.
- However, due to the difference in physico-chemical properties like viscosity, the productivity drops significantly for bilge water compared to salt water.

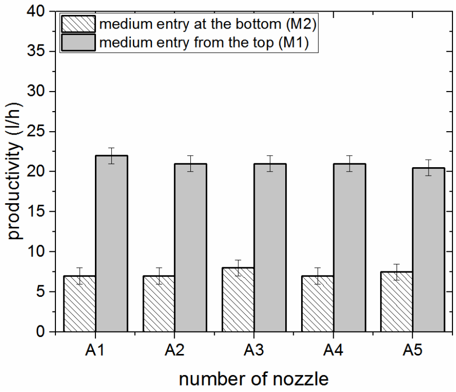

Figure 10: Productivity for air entry in nozzle A1 to A5 (striped: medium entry from bottom nozzle, gray: medium entry from top nozzle); mixture of 330 l of tab water and 190 l of bilge water

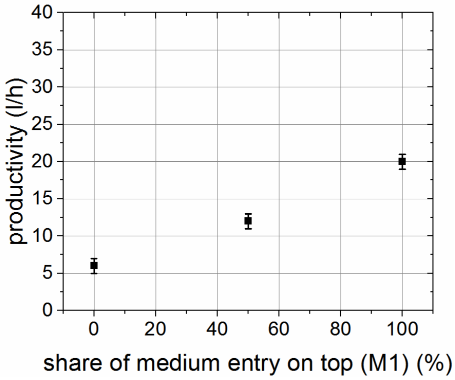

Figure 11: Productivity depending on share of medium entry on top (M1); mixture of 330 l of tab water and 190 l of bilge water

Acknowledgement
The author wants to thank Dr. Christoph Kern and Birgit Brunner from the Chair of Chemical Engineering within the Center of Energy Technology for the analytic measurements and their input on the chemical analysis of bilge water. The work is partly financed by the German Federal Ministry of Economic Affairs and Energy within the Central Innovation Programme for SMEs due to an enactment of the German Bundestag. Furthermore, the ICP-AES is a financial support of the Bavarian State Ministry of Education, Science and the Arts within the framework TechnologieAllianzOberfranken (TAO). The author gratefully acknowledges the funding.

Nomenclature

A	Air	MED	Multi-effect Distillation
C	Carbon	MSF	Multi-stage Flash Distillation
H	Hydrogen	N	Nitrogen
HDH	Humidification Dehumidification	RO	Reverse Osmosis
ICP-AES	Inductively Coupled Plasma - Atomic Emission Spectrometry	S	Sulfur
		TVC	Thermal Vapour Compression
M	Medium		

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