MATHEMATICAL MODELING AND SIMULATION OF A HEAT PUMP WATER DESALINATION PROCESS

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Abstract. *Numerous communities in Brazil show a lack of drinking water. There are many resources available for its purification. It is clear that the technological mastery of each alternative is a strategic issue for Brazil. The aim of this paper is the modeling a system for obtaining pure water from brackish or sea water through a heat pump, with mechanical compression of an auxiliary fluid. There were employed the techniques of material and energy balances, coupled with thermodynamic predictions and analysis. A system where the heat exchangers for preheating the supply is independent from the compression cycle was studied, operating thanks to the final cooling of de product and the waste of the process. The auxiliary fluid is considered pure water. Two concentrations were considered for the saline aqueous solution, 0.002 kg / kg and 0.034 kg / kg, respectively simulating the brackish water unfit for human consumption and sea water. The different simulations resulted on energy consumption for desalination between 10.3 and 30.4 kWh/m^3 of pure water produced. For brackish water, it were simulated yields (product flow / feed flow rate) as high as 98%.*

Keywords: Desalination, sea water, brackish water, heat pump, evaporation.

1. INTRODUCTION

A huge amount of water available in Brazil and worldwide is unfit for consumption only due to high concentration of salts present. Thus, the best solution to the question may pass by the techniques of desalination, which presently can now compete economically with those of conventional use of available water resources. Recently, Reddy and Ghaffour (2007) conducted an interesting economic and production study of the various types of desalination employed worldwide. With the beginning of it's widespread use in 1960, in 2005 the installed desalination capacity was estimated at 53.69 x 10^6 m3 per day and the cost of treatment has come close to conventional, even in countries with no lack of water resources. A brief description of the alternatives to desalination was made by Ettouney and El-Dessouky (2001), Milcent *et al.* (2009), and others. The multi-stage evaporation (MED) produces water at a cost of US$ 0.55 to US$ 0.70/m^3 and requires an investment of around US$ 850.00 per m^3 per day. This is currently the most economical thermal technique for the production of drinking water. Reverse osmosis (RO) investment is of US$ 500.00 to 1000.00 / m^3 per day, and the cost of water produced depends strongly on the characteristics of the feeding, being less than US$ 2.20 / m^3 and even less than US$ 0.50 / m^3 in favorable conditions.

The techniques of desalination by vapor compression (VC) are limited to small installations, producing less than 800m^3/day. It is estimated that the total installed capacity using such technology is around 2.0 x 10^6 m^3/day. The desalination heat pump can be considered a variant of VC. It was previously studied by Slesarenko (2001) amongst other authors. These units require low investment and low operating costs. They present simple procedures for operation and maintenance, high thermal efficiency, low pumping needs and consumption of chemicals, as well as flexibility, reliability and stability in operation. These qualities indeed, are extended to most, if not all the well designed thermal desalination. While desalination by VC, already studied by Milcent *et al.* (2009) and others, requires that the steam circulates by the compressor, in this case the product of the process, the heat pump cycle by closed vapor compression, gives freedom of choice of the working fluid. In addition, recently Milcent *et al*. (2010) have compared two alternative systems for obtaining drinking water, using a heat pump by compression cycle. Under similar conditions, it was shown that the included system, although slightly constructively more simple, has a significantly higher energy demand that the exclusive system. The latter, therefore, is the system presented in this work. Heat pumps, similar to conventional VC desalination, are preliminarily indicated to the service of small communities. The durability of installation, analogous to VC, is estimated as being of about twenty years. This value is significantly above the average lifetime of membranes. The system tends to dispense highly qualified workers due to the qualities already enumerated. It is environmentally and economically more interesting in that it practically exempts the chemicals consumption. The electrical power required for the operation may come from clean sources such as hydroelectric, photoelectric cells or wind. Its design, construction and constituent parts may be made or originate entirely in this country. Finally, the proposed system does not generate thermal pollution.

National efforts have been made for the purification of brackish water by reverse osmosis. This is, however, one of many alternative techniques available for obtaining drinking water from such a source. Globally evaporative units, desalinizing sea water, equal in capacity to those based on semi-permeable membranes. In the first case, the operating procedures tend to be simple and reliable, with low consumption of auxiliary chemicals. The durability is high and maintenance facilities tend to be simple.

The objective of this work is the modeling of a system for obtaining drinking water from brackish or sea water, through a heat pump, with mechanical compression of auxiliary fluid. Such system might be considered ideal for meeting the needs of small communities, even those lacking in high specialization labor.

2. METHODOLOGY

The methodology used covers the techniques of material and energy balances associated with thermodynamic predictions. These, among other parameters, show the relation between impure water processed and desalinated water produced, as well as the power consumption of the proposed facility. The system studied is schematically represented in Fig. 1. The proper cooling of the purified water and the waste is of primary importance to avoid thermal pollution, and allows the reduction of power consumption and consequent reduction of cost of the produced water.

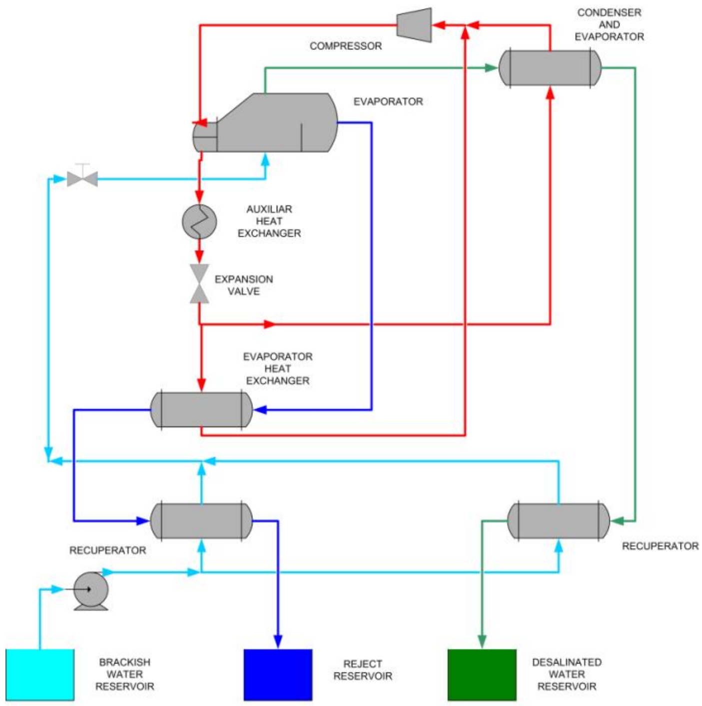

Figure 1. Desalination system proposed.

3. MODELING ON STEADY OPERATION

The mass flow of saline water fed to the system, its concentration and the final concentration for the waste were considered independent variables. Other variables arbitrarily set for the simulations were the differences in temperature between the fluids circulating inside the heat exchangers and the thermodynamic efficiency of the compressor. It was used a low processing capacity, compatible with the assistance of needs of small communities, of 1.39 kg / s. The salt water was considered as having 0.002 kg of salt / kg and sea water 0.034 kg of salt/ kg. For purposes of calculating, the drag of salts by steam coming from the evaporator is negligible. High salt concentrations in the waste are avoided in the usual processing practice to eliminate or minimize fouling. The valve expansion was considered adiabatic. The temperature differences of the output fluids in all heat exchangers was fixed at most simulations as 5 K. It was inserted into the model the definition of compressor efficiency to predict the non-ideality of compression. The expression for determining the elevation of the boiling point of a saline solution is given by El-Dessouky *et al.* (2000). Below 0.002 kg of salt/ kg, the increase on the boiling point is so low (b.p.e <0.5 K), that it was considered valid to extrapolate the lower validity limit of concentration of the equation given. Of all simulations, none show the pressure within the evaporator exceeding 200 kPa.

4. RESULTS

In all cases the surrounding temperature was set constant at 298 K. Rising this temperature decreases the size of the heat exchangers for preheating the feed, increases the temperature of the disposal of waste and purified water required and under the conditions of the proposed system does not change the power consumption of the installation.

Figures 2 and 3 present a summary of the results. An increase in the efficiency of the compressor reduces power consumption. The same effect is observed with increasing flow rate of waste (reduction of productivity), and decreasing temperature between those of the fluids in heat exchangers of the cycle. The energy consumption in the desalination of sea water is greater due to the undesirable effect of raising the boiling point proportionally to the concentration of salt solutions. In the range of data in Fig. 2, the intake is between 10.26 kWh/m^3 of pure water produced and 30.32 kWh/m3 p.w.p. whereas in the data of Fig. 3, of between 13.87 kWh/m^3 and 30.41 kWh/m^3 p.w.p. For brackish water recoveries were considered up to 98%.

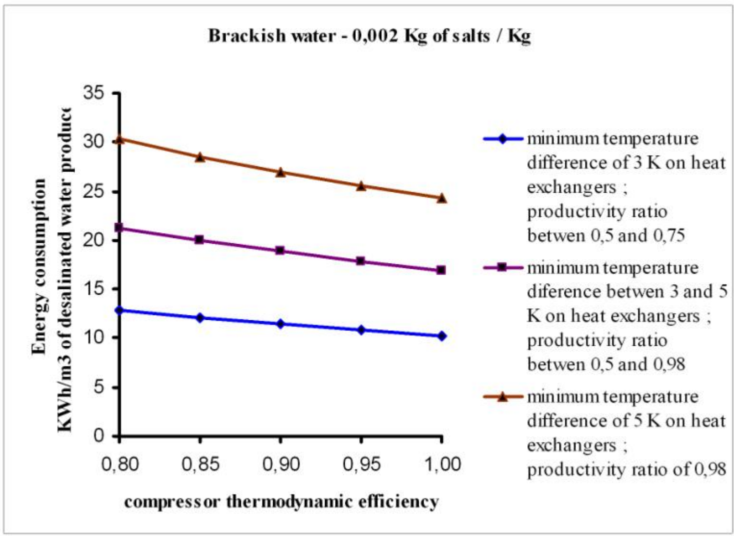

Figure 2. Energy consumption in relation to the compressor efficiency for simulations with brackish water. Concentration of 0.002 kg of salts/kg and absolute pressure in the evaporator of 121 kPa.

The lower energy consumption for the desalination of sea water (11.57 kWh/m^3 p.w.p.) was obtained with maximum compressor efficiency, productivity of 50% and temperature difference of 3 K. For the evaporation of brackish water, the lower consumption, 10.26 kWh/m^3 p.w.p. was obtained considering the maximum compressor efficiency, the lowest tested yield (50%) and also a temperature difference of only 3 K.

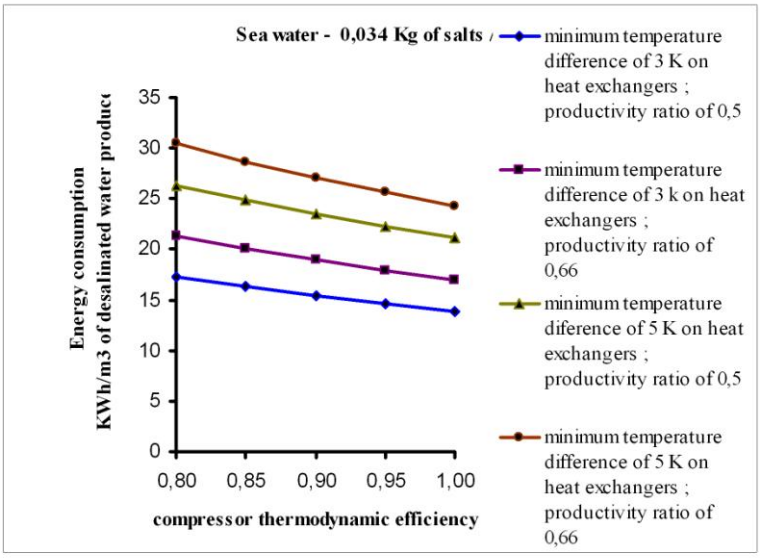

Figure 3. Energy consumption in relation to the compressor efficiency for simulations with sea water. Concentration of 0.034 kg of salts/kg and absolute pressure in the evaporator of 121 kPa.

Working with brackish water is more economical than sea water, as in the first case the final solutions are more diluted, with smaller increment to the boiling point. In the simulation of the same case, reducing the compressor efficiency to 80% resulted in energy consumption increasing to 12.82 kWh/m^3 p.w.p.. Changing the productivity from 50% to 75%, still with only 80% efficiency in the compressor, the simulation shows a slightly higher consumption of 12.97 kWh/m^3 of pure water produced. As a result, it is possible to significantly increase the productivity of a plant for the purification of brackish water without major financial changes, due to low variation of the boiling point rise within the wide range of recovery. The boiling point rise is unfavorable because it forces a higher temperature of condensation of the circulating fluid.

It was determined, for comparison, the amount of energy used by a single evaporator to accomplish the same proposed work without the use of any device for heat recovery. In this case the consumption rises of 10.26 kWh/m^3 p.w.p. to 808.97 kWh/m^3 p.w.p..

The effect of increasing the evaporation pressure in the system was analyzed. In this case, the boiling temperature of the aqueous solution increases and also slightly increases the temperature difference between the condensation and evaporation in the cycle, due to the small increase on the boiling point rise and also the absolute temperature increased in the cycle. In the case studied, the fluid within the heat pump is also water. If the evaporation occurs at a pressure below 121 kPa, the lower pressure of the working fluid within the cycle is less than the ambient. This fact is considered undesirable because of the ease on the inlet of inert air. With the increase in pressure in the evaporator evaporation, the absolute pressure in the cycle also increases. In the simulations carried out their magnitude remained satisfactory. The temperature of the superheated vapor leaving the compressor increased and the energy consumption had mild reduction.

The maximum temperature in the system did not exceed 160 K. The compression ratio was less than 1.7 in all cases. A low compression ratio indicates both a low power consumption in a compressor as well as a reduced consumption in the compression closed cycle with circulating fluid. The lack of a perfect equilibrium between the amount of heat transferred and received by the heat pump, gives rise to a surplus amount of heat in the cycle, offset by the auxiliary heat exchanger. The simulations show that a fit of operating conditions turns such excess negligible. The more diluted the concentration in the evaporator, the lower the boiling point rise. With this, the condensing temperature of the fluid in the cycle becomes smaller, which in turn, reduces the temperature difference in the cycle, the compression ratio, the power consumption and the overheating. With a lower production and thus less water evaporated, the compression cycle is less than required or smaller and the amount of working fluid is also reduced. The reduction in the temperature difference established in the heat exchangers reduces the extreme temperature difference on the cycle and therewith reduces the rate of compression and power consumption. High concentrations of the boiling solution in the evaporator result in equally high yields of installation and reduced waste flow. However, the salt concentration increases and the fouling can become more relevant. The smaller the temperature difference between the fluids inside the heat exchangers, the larger thermal exchange areas required. For brackish water recoveries were considered up to 98%.

5. CONCLUSION

This paper studies the obtainment of desalinated water from sea water or brackish water by employing heat pump by compression cycle. This technique may be proven effective for water purification units of small and medium sizes. It is suggested a national research effort exploring the various alternatives available for desalination, as the literature review demonstrates that there is no single solution to the matter.

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