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Multi Stage Flash Desalination with Direct Mixing Condensation

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Multi Stage Flash desalination technology has been a leading technology in the desalination market for the last four decades. However as a result of the continuous increase of costs for the special materials required for the tube bundles the share of MSF technology in the market is nowadays steadily shrinking.

Aim of the present work is to present a novel configuration for the MSF process. In the proposed arrangement evaporation occurs in a multi stage vertical column filled with packing material to enhance the achievement of flashing equilibrium in each stage, while condensation occurs in a second column through direct mixing with a colder water stream. Thermal integration for the recovery of condensation latent heat is performed by an external plate-and-frame heat exchanger, which reduces dramatically the quantity of special materials required at the same time significantly enhancing the heat transfer.

A preliminary analysis of feasibility and potentials of such process is presented.

1. Introduction

In the last four decades desalination industry has grown at a dramatically fast rate, thanks to a number of different technologies. Among them, the Multi Stage Flash (MSF) technology covers almost 50% of total world desalination production, and represents the leading technology in the Gulf Countries. However, in the last decade, the continuous increase of costs for the special materials required for the tube bundles of MSF plants has increased the investment costs for new plants and for the revamping of old ones, thus reducing the competitiveness of MSF technology in the world desalination market.

In the MSF process vapour is produced from a hot brine by a sudden reduction in pressure, which generates the flashing phenomenon. Evaporation takes place already at the entrance of each stage and from the bulk of the liquid solution, thus avoiding the presence of evaporation surfaces and reducing the risk of scaling formation.

The generated vapour takes its latent heat of evaporation from the liquid itself, which is in turn cooled. Once entered the subsequent stage, the saline solution undergoes a further reduction of pressure, thus repeating the evaporation by flashing stage by stage until the minimum brine temperature is achieved in the last stage.

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The vapour produced in each stage condensates on the external surface of a tube bundle positioned above the flashing space, transferring its latent heat of condensation to a colder stream, typically constituted by the feed brine itself, which is in turn pre-heated.
The pre-heated brine eventually passes through a brine heater where it reaches its Top Brine Temperature (TBT) before entering the first flashing stage. In the industrially adopted brine circulation configuration, only a small portion of the cooling stream in the last 2-3 stages (heat rejection section) is used as seawater make-up, which is mixed with some of the brine exiting from the last stage and is then used to feed the unit (in the heat recovery section).
The temperature operating range, i.e. the TBT and the temperature of the last stage is typically between 105-115°C for TBT (higher values can generate $CaSO_4$ scaling inside the tube bundle) and 35-45°C for the last stage (depending on cold seawater temperature). These values can significantly affect the overall performance of the process, as a larger T-range would generate a larger Gain Output Ratio, defined as the ratio between the produced distillate and the consumed steam (kg/kg).
A possible breakthrough for this technology can be the substitution of the condensation tube bundles with a more effective condensation device, in which there is no need for large quantities of expensive metal alloys and which could also minimise the problem of corrosion and scaling often occurring in the tube bundles of the lowest and highest temperature stages of MSF units respectively.
In the present work, a new configuration of the MSF process is proposed, where vapour condensation occurs by direct mixing within a cold distillate stream in counter-current flow. Final heat recovery is performed by plate heat exchangers, thus achieving a good thermal integration of the overall process. Several works have been presented in the open literature on the advantages of direct contact condensation (Sideman and Moalem, 1974) and on its possible use for the integration within a MSF process (Kohl et al., 1976; Dick, 1975; Walker et al., 1967). Here a novel process scheme is presented along with some preliminary analysis of feasibility and relevant advantages/ disadvantages.

2. MSF desalination with direct mixing condensation

As shown in Fig.1, in the proposed process scheme the evaporation takes place in a vertical stack Multi Stage Flash unit (2) of *N* flashing stages. A bubble column (3) receives the vapour produced in each stage thus allowing its condensation through direct mixing with a distillate stream flowing from the top to the bottom of the column, where the necessary pressure gradient is generated by the hydrostatic head itself. In this way vapour transfers its latent heat of condensation to the liquid stream being heated. Vapour from the first flashing stage, at maximum pressure and temperature, is injected in the first stage (bottom) of the condensing column, where it condenses by mixing with the liquid arriving to the bottom of the column, which then exits efficiently pre-heated. In order to keep the vacuum at the top of the bubble column and to extract non-condensable gases accumulating at the top of the column itself, a steam-ejector (5) with a down condenser (6) or a hydro-ejector are required. Finally, the hot distillate exiting from the column bottom, enters a plate heat exchanger (1) where it is cooled down (in order to obtain again a stream to be fed to the top of the bubble column) performing the pre-heating of feed seawater. To allow a better control two pre-heaters can be foreseen, simulating the “heat recovery” and the “heat rejection” sections of BC-MSF plants.

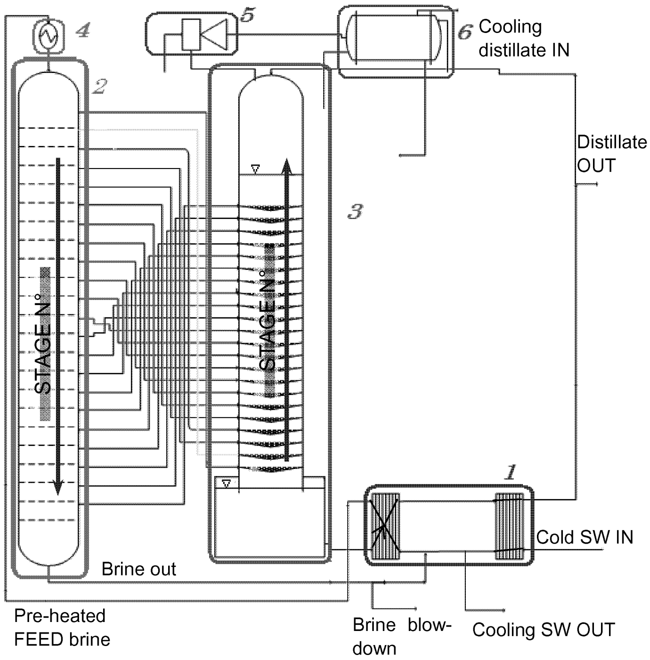

Figure 1: Operating scheme of the novel MSF configuration with condensation through direct mixing. 1) Plate heat exchangers (for thermal integration); 2) Flashing column; 3) Condensation column; 4) Brine heater; 5) Thermo-ejector (for non-condensables); 6) Final condenser (for collecting vapour from the thermo-ejector)

3. Performance analysis of the process

To preliminary assess the feasibility of the proposed process and analysing the performance parameters, a mathematical model has been implemented based on mass and heat balance equations. The attention has been focused on the three main units of the plant, i.e. the Multi Stage Flash evaporator, the bubble column condenser and the plate and frame heat exchanger. A nominal capacity of 10,000 m^3/d of distilled water and a feed seawater salinity of 37 gr/lt have been set. At this stage no focus has been put on the plant design features, as this will be objective of future analysis.

The following simplifying assumptions have been taken into account: 1) salt free vapour produced in the flashing stages; 2) no heat losses in the units and colleting pipes; 3) non-condensable gases are neglected; 4) Non Equilibrium Allowance (NEA) in the flashing stages is neglected; 5) Boling Point Elevation and Temperature losses through demisters have been taken into account as “thermodynamic losses” in flashing stages.

Moreover some operating parameters have been fixed, i.e. seawater temperature of 30°C (typical of North African and Gulf Countries), brine blow-down temperature of 40°C and salinity of 70 gr/lt, heat exchangers ΔT_{lm} of 2°C. On the other side, the number of stages and the Top Brine Temperature (TBT) were varied for the performance analysis of the process. The standard configuration for performance analysis was set with 22 stages, a TBT of 110°C and inter-stage temperature drops assumed constant along the flashing stages. Fig.2 shows temperature and pressure profiles along the unit, useful also for the analysis of the bubble column operation.

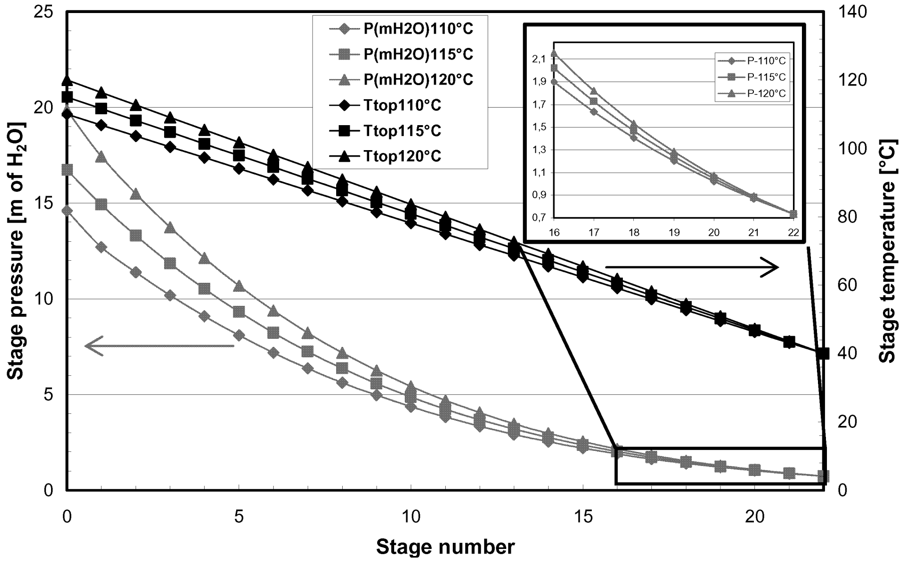

Figure 2: Temperature and pressure profiles along the flashing stages for three different TBT (110°C, 115°C and 120°C). In the inset an enlarged view of pressure profiles in the last stages

The condensation column constitutes the most innovative part of the proposed idea. The extremely efficient heat transfer in direct contact condensation, indeed, allows the vapour condensation keeping a minimum driving force and avoiding the use of expensive and complex stage-by-stage condensing tube bundles. The column has been ideally divided into a number of stages equal to the flashing stages, each eight equal to the interstage ΔP (expressed in m of water column) of relevant flashing stage. Stage numbering starts from the first (top) stage at the lowest pressure and temperature to the last (bottom) stage at the maximum temperature and atmospheric pressure. In order to take into account the complex phenomena (Molin et al., 2009) of bubble rise/condensation/cooling, a bubbling regime has been assumed for a column diameter of 3.5mt. The condensation rate and, thus, the bubble shrinking rate have been calculated by:

$$q_{b-l} = \overset{\bullet}{m}_c \, \lambda_v = h \cdot \pi \cdot d_b^2 (T_v - T_l) \ (2), \qquad \text{with } \overset{\bullet}{m}_c = -\rho_v \cdot V_b \cdot \frac{\pi}{6} \cdot 3 d_b^2 \left(\frac{d(d_b)}{dx} \right) \qquad (3)$$

where the rising velocity and heat transfer coefficient were calculated by literature correlations (Sideman, 1974). The above equations have been suitably rearranged and, together with the heat balance equation to take into account the temperature increase of the cooling water due to vapour condensation, have been implemented and solved.

For the sake of brevity model equations have not been reported. Fig. 3 reports the condensation heights of vapour bubbles for comparison with the ideal condensing stage height for the standard case of TBT=110°C and 22 stages and with a temperature difference of 1 °C between condensing vapour and cooling liquid in the first stage. It is worth noting how the estimated values of condensing height are in all cases significantly smaller than the ideal stage height, thus confirming the effectiveness of direct contact condensation.

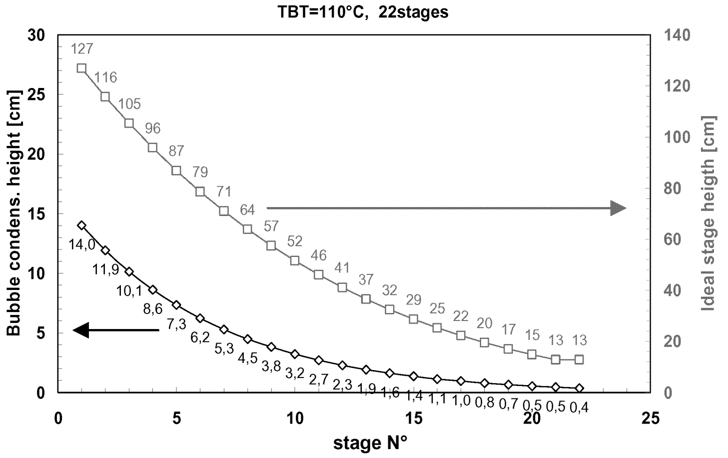

Figure 3: Estimated vapour bubble condensation height in the stages compared to the ideal stage height computed from pressure profiles shown in Fig.2

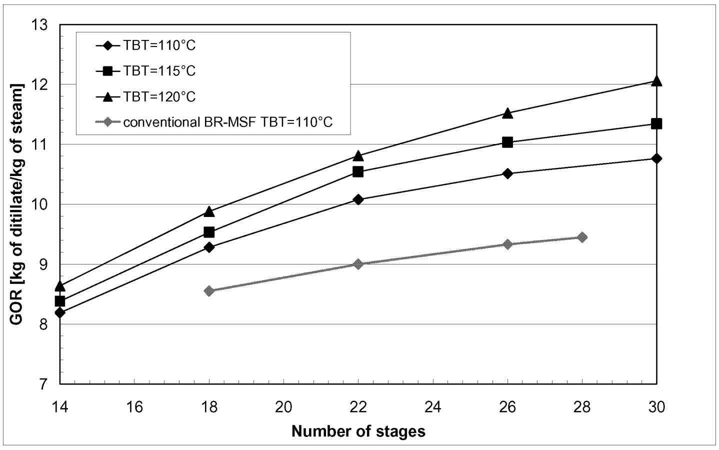

Figure 4: Estimated Gain Output Ratio of the process as a function of number of stages and Top Brine Temperature. The red line shows a similar trend predicted for a conventional BR-MSF unit (source: El-Dessouky and Ettouney, 2002)

A plate HX is used to recover the condensation heat from the distillate stream and a second plate HX is used to further cool the distillate before recirculating it to the condensing column, with a recycle of the exiting brine from the flashing column.

The process model equations have been solved using Matlab® and allowed to analyze the performance of the process varying the above mentioned operating parameters. In Fig. 4 the estimated Gain Output Ratio is reported as a function of the number of flashing stages and the Top Brine Temperature (TBT), also in comparison with a similar trend predicted for a conventional BR-MSF unit (El-Dessouky and Ettouney, 2002). Results show GOR values increasing with the number of stages and TBT, in accordance with trends observed for conventional MSF units. Moreover, notwithstanding the double step here required for the thermal integration (condensation column and HXs), GOR values are still comparable or even higher than conventional ones, especially for larger number of stages, thus indicating a good potential for further investigation and analysis of the proposed process scheme.

4. Conclusions

A theoretical analysis of a novel configuration for a multi stage flash desalination unit is presented. The novelty consists in the coupling of flashing stages with a condensation column operating through the direct mixing of vapor with fresh water. A full thermal integration is also adopted in order to keep a high energetic performance of the process. A first analysis of process performance has confirmed the feasibility of condensing stages within the bubble condensation column and has shown interesting trends of performance parameters compared with conventional MSF units. Next steps will focus on the study of the technical plant practicability and the economical analysis for a more accurate assessment of the concept idea feasibility.

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