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# Modelling and Simulation of MSF Desalination Plant: The Effect of Venting System Design for Non-Condensable Gases

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The presence of non-condensable gases (NCGs) such as carbon dioxide, nitrogen, oxygen, and argon caused by air leakages to stages and the release of dissolved gases in brine have, even small proportions, great effect on the heat transfer rate at the vapour side of the stage condensers. Due to the low conductivity of these gases, they work as insulation material and decrease the heat transfer rate and in turn they affect the plant performance. In this work, a dynamic mathematical model is developed and implemented to analyse the effect of NCGs in MSF desalination process using gPROMS software. The model is based on coupling the mass balance, energy balance and heat transfer equations with supporting correlations for physical properties calculations. The effect of NCGs on heat transfer rate and the variation of the amount of NCGs from stage to stage are studied. The present model is validated against actual plant data collected from literature. The results showed a good agreement with actual data. The results showed that the concentration of NCGs in the vapour space depends on the location of venting points and the rate release of the NCGs. Also the results revealed that the overall heat transfer coefficient (OHTC) is affected by high concentration of NCGs. The optimum location of the venting system can be obtained by variation of the venting stages.

## 1. Introduction

Fouling and the release of non-condensable gases NCGs are of great concern for the performance of the thermal desalination process. In thermal desalination process such as multistage flash desalination (MSF), the performance of plant is mainly affected by the condition of heat transfer surfaces, therefore, accumulation of fouling and NCGs can reduce the efficiency of the heat transfer process resulting in poor plant performance. The NCGs, in particular, do not have the ability to condense inside a condenser, unlike steam, and thus they remain in the gas phase resulting in a serious impact on the performance of thermal desalination of seawater. Even low concentrations of NCGs gases can cause a severe reduction of the overall heat transfer coefficient and hence the performance of desalination process. The most common NCGs in the MSF desalination plants are air ($N_2$ and $O_2$), argon (Ar) and $CO_2$ and they are present in the plants due to the leakage of ambient air through flanges, release of carbon dioxide $CO_2$ from decomposition of the bicarbonates, and dissolved gases in the seawater feed (Said et al., 2010). Removing these gases through venting system is vital to the efficient operation of all desalination plants.

There are several studies concerning the release of NCGs in thermal desalination processes. Seifert and Genthner (1991) and Genthner and Seifert (1991) developed analytical model to estimate the amount of NCGs in the MSF chambers and their variation from stage to stage depending on the venting points. The authors studied the effect of NCGs on the vapour side heat transfer coefficient ($h_o$) by varying NCGs concentration in the first stage of the MSF plant. Genthner et al. (1993) studied the effect of NCGs on the vapour side heat transfer coefficient as a function of radial tube bundle location by varying the NCGs concentration in the first stage. For better understanding of $CO_2$ release in MSF process, Said et al. (2011) used neural networks (NN) to develop a correlation for calculating the first and second dissociation constant of carbonic acid in sea water as function of temperature and salinity. However, despite the

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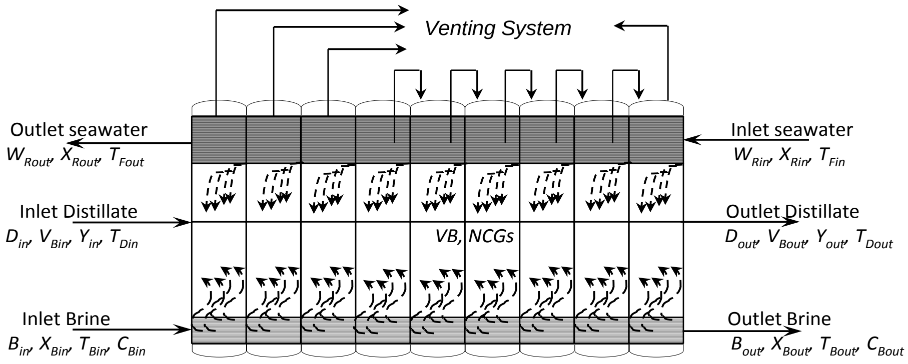
importance of these studies, they were developed and studied on their own but have not been a part of the whole MSF process performance evaluation.
The mathematical models of MSF process are well known in the literature and established and developed using the basic law of thermodynamics. Among these studies, a very limited number of publications considered the effect of NCGs in their model. Reddy et al. (1995) included the amount of NCGs in the mass balance equations for the first time. Recently, Alfulaij et al. (2011) also considered NCGs in their model based study in gPROMS. Recent studies by Alasfour and Abdulrahim (2009) and Said et al. (2010) included NCGs correlations in their models to study the effect of NCGs on the heat transfer rate however. Previous studies focused on the effect of NCGs on the heat transfer rate however; a fixed value for the amount of NCGs was considered in every stage. In reality, an installation of venting system plays an important role on increasing the heat transfer rate by extracting the NCGs to the atmosphere or to the evacuating system. The evacuated system is installed in series for some stages and in parallel for other stages, making the amount of NCGs variable from stage to stage. While Alasfour and Abdulrahim (2009) used a fixed value for the NCGs concentration, Said et al. (2010) used different values of NCGs but these values are still constant for all stages. In reality, an installation of the venting system at different points makes the amount of NCGs vary from stage to stage.
In this work, a dynamic mathematical model is developed and implemented to analyse the MSF desalination process using gPROMS software. The model includes the mass flow rate of NCGs in the material balance equations with supporting correlations for physical properties calculations. The release rate is studied using Henry's law.

## 2. Process description

When the brine enters the flash chambers in MSF plants, the vapour and NCGs evaporate due to the sudden reduction of the pressure. The vapour will release the latent heat to the process and condense down to condensate in the heat transfer area, but the NCGs do not condense and thus reduce the available heat transfer area. At high temperature, as in the case of MSF, the NCGs mainly $CO_2$ become less soluble and as a result most of these gases are evaporated in the first MSF stage, the rest in the following stages (Genthner et al., 1993).
Due to condensation process around the tubes bundle, vapour moves toward the heat transfer surface and condenses. The NCGs move with the steam up to the wall where they accumulate (Semiat and Galperin, 2001). The NCGs are transported by diffusion and convective mass transfer back to the bulk vapour space producing an additional heat transfer resistance between the vapour and the tubes bundle (Genthner and Seifert, 1991) and thus, venting them is required to reduce the concentration of NCGs.In MSF plants, The NCGs vented from the condenser tube bundle can be connected in series where the gases cascade from stage to stage and finally vented to the evacuated system, or in parallel where the gases from each stage are vented directly to the evacuated system (Darwish et al., 1995). Most of the MSF plants use a combination of parallel and series system due to the drawbacks of using a particular type. Figure 1 shows the venting system of MSF plant where the first few stages are connected in parallel due to high concentration of NCGs while the rest of the stages are connected in series.

## 3. Mathematical model

Here, the dynamic models developed by Reddy et al. (1995) and Alfulaij et al. (2011) are refined with new overall heat transfer coefficient correlation reported by El-Dessouky and Ettouney (2002) and is used to study the effect of NCGs. Also the model is supported by physical properties correlations reported by El-Dessouky and Ettouney (2002). While the air is almost evaporated (more than 95 %) in the first stage, the $CO_2$ is continuously liberated in small amount in each stage due to the low degassing process of $CO_2$ and high solubility of $CO_2$ compared to other gases (Genthner et al., 1993). Therefore in this model, for the latter reason, the NCGs dissolved in seawater are assumed to be only $CO_2$. Henry's law and its constant reported by Carroll et al. (1991) to calculate the equilibrium concentration of the $CO_2$ in brine is used. It is important to mention that due to the limitation of Henry's law the sea water is assumed to be dilute solution. Also the NCGs released from chemical reaction is neglected and only physical phenomenon of NCGs release is considered. The stage can be modelled as a vessel and then all stages are modelled as chain of vessels. Figure 1 shows a schematic diagram of flashing stages and the process model equations. For the sake of compactness, the model equations are presented here.




Stage Model

Mass balance in the flashing brine:

$$\frac{dM_B}{dt} = B_{in} - B_{out} - V_B - NC \quad (1)$$

Salt balance : $$\frac{dM_S}{dt} = B_{in} \times X_{Bin} - B_{out} \times X_{Bout} \quad (2)$$

NCGs balance in brine:

$$\frac{dM_{BNCGs}}{dt} = B_{in} \times C_{Bin} - B_{out} \times C_{Bout} - NCGs \quad (3)$$

Enthalpy balance in flashing brine:

$$\frac{dM_B H_B}{dt} = B_{in} \times H_{Bin} - B_{out} \times H_{Bout} - V_B \times H_{VB} - NCGs \times H_{NCGs} \quad (4)$$

$$H = Cp \times (\Delta T), \quad Cp = f(X_B, T) \quad (5,6)$$

Mass balance for the distillate:

$$\frac{dM_D}{dt} = D_{in} + C_{VD} - D_{out} \quad (7)$$

Enthalpy balance in distillate tray:

$$\frac{dM_D H_D}{dt} = D_{in} \times H_{Din} + C_{VD} \times \lambda_v - D_{out} \times H_{Dout} \quad (8)$$

Mass balance in vapour space:

$$\frac{dM_V}{dt} = V_B + V_{in} + NCGs - C_{VD} - V_{out} \quad (9)$$

NCGs balance in vapour phase:

$$\frac{dM_{VNCGs}}{dt} = NCGs + (V_{in} \times Y_{in}) - (V_{out} \times Y_{out}) \quad (10)$$

Enthalpy balance in vapour:

$$\frac{dM_V H_V}{dt} = (V_B \times H_V) + (NCGs \times H_{NCGs}) + (V_{in} \times (1 - Y_{in}) \times H_{Vin} + (V_{in} \times Y_{in} \times H_{NCGsin}) + (D_{in} \times H_{Din}) - (D_{out} \times H_{Dout}) - (V_{out} \times Y_{out} \times H_{NCGsout}) - (V_{out} \times (1 - Y_{out}) \times H_{Vout} \quad (11)$$

Overall energy balance on stage:

$$W_R \times Cp_w \times (T_{Fin} - T_{Fout}) = D_{in} \times H_{Din} + C_{VD} \times \lambda_v + (V_{in} \times (1 - Y_{in})) \times (Hv_{in} + \lambda_v) + (V_{in} \times Y_{in} \times H_{NCGsin}) \quad (12)$$

*(Temperature leaving the stage is reference temperature)*

Heat transfer equation:

$$W_R \times Cp_w \times (T_{Fin} - T_{Fout}) = U \times A \times LMT \quad (13)$$

(In rejection stages, $W_R$ is replace by $W_S$ and $X_R$ is replaced by $X_S$)

$$LMTD = \frac{(T_{Fout} - T_{Fin})}{\ln\left[\frac{(T_D - T_{Fin})}{(T_D - T_{Fout})}\right]} \quad (14)$$

Distillate and flashing brine temperature correlation:

$$T_B = T_D + BPE + NEA + \Delta T_{DEM}, \quad T_D = T_V \quad (15,16)$$

Brine Heater Model

Mass and salt balance: $W_R = B_0; \ X_R = X_{B0}$ (17,18)

Enthalpy balance:

$$W_R \times Cp_w \times (T_{B0} - T_{F1}) = W_{steam} \times \lambda_{steam} \quad (19)$$

Heat transfer equation:

$$W_R \times Cp_w \times (T_{B0} - T_{F1}) = U_h \times A_h \times LMTD_h \quad (20)$$

$$LMTD_h = \frac{(T_{B0} - T_{F1})}{\ln\left[\frac{(T_{steam} - T_{F1})}{(T_{steam} - T_{B0})}\right]} \quad (21)$$

Overall heat transfer coefficient

$$\frac{1}{U_o} = \left(\frac{d_o}{h_i d_i}\right) + \left(R_{f,i}\frac{d_o}{d_i}\right) + \left(\frac{d_o}{2k_t}\right) Ln\left(\frac{d_o}{d_i}\right) + R_{f,o} + \left(\frac{1}{h_o}\right) \quad (22)$$

Vapour side heat transfer coefficient

$$h_o = 0.725 \times \left[\frac{g k_L{}^3 \rho_L(\rho_L - \rho_V)\ \lambda_V}{\mu_L d_o (T_D - T_W)}\right]^{0.25} \times C_1 \times C_2 \quad (23)$$

$$C_1 = 1.23795 + 0.353808N - 0.0017035N^2 \quad (24)$$

$$C_2 = 1.0 - 34.313(Y) + 1226.8(Y)^2 - 14923(Y)^3 \quad (25)$$

$$N = 0.564\sqrt{N_t}, \quad N_t = \frac{4W_R}{\pi d_i{}^2 \rho_b v_b} \quad (26,27)$$

Water side heat transfer coefficient

$$h_i = (3293.5 + T_F(84.24 - 0.1714 \times T_F) - X_R(8.471 + 0.1161 \times X_R + 0.2716 \times T_F))/ \left(\left(\frac{d_i}{0.017272}\right)^{0.2}\right)\left((0.656 \times v_{vel})^{0.8}\right) \left(\frac{d_i}{d_o}\right) \quad (28)$$

Henry's Law

$$C_{MOLEQ} \times He = Y_{MOL} \times P \quad (29)$$

Henry's constant for $CO_2$:

$$Ln\left(\frac{He}{MPa}\right) = -6.8346 + 1.2817 \times \frac{10^4}{T} - 3.7668 \times \frac{10^6}{T^2} + 2.997 \times 10^8/T^3 \quad (30)$$

*Figure 1: Schematic of MSF venting system with process model*

## 4. Results and discussions

The simulation results are validated against the real data of Azzour desalination plant, which is collected from Alasfour and Abdulrahim (2009). Due to the lack of dynamic data, the validation process is only for steady state data. The model is run for approximately 3 h to reach the steady state and then the results are validated. A good agreement is obtained between the simulation results and the plant data for the brine and distillate flow rates as shown in Figure 2. Also the brine temperature and pressure profiles are plotted in Figure 3. Figure 4 shows the amount of NCGs released per stage. As it can be seen, most of the $CO_2$ liberated in the first few stages due to the low solubility of $CO_2$ at high temperature.

### 4.1 Variation of venting points

Said and Mujtaba (2010) reported that the NCGs has no significant effect on OHTC unless the concentration of NCGs exceeds 0.05 (wt. %). Also, they reported that from 0.05 up to 0.06, a significant decrease in OHTC occurred. Therefore, in this model, the venting points were assumed to be installed in different stages to avoid the increase of NCGs over 0.05. In most MSF plants, venting points in the first stage and last stage are essential. The former is due to high release of NCGs in the first stage and the latter is required to vent the accumulated gases from the rest of stages. Overestimate of the number of venting points result in unnecessary vapour losses with the vent and a higher energy consumption of the venting system. For a constant fouling factor and fixed value for dissolved gases in the entering seawater, following observation are made:

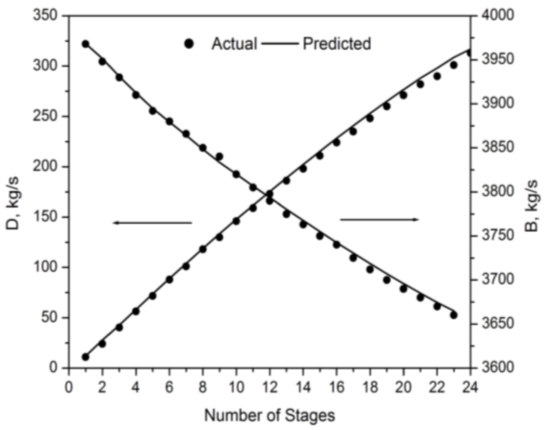



*Figure 2: Distillate and flashing brine flow rate*

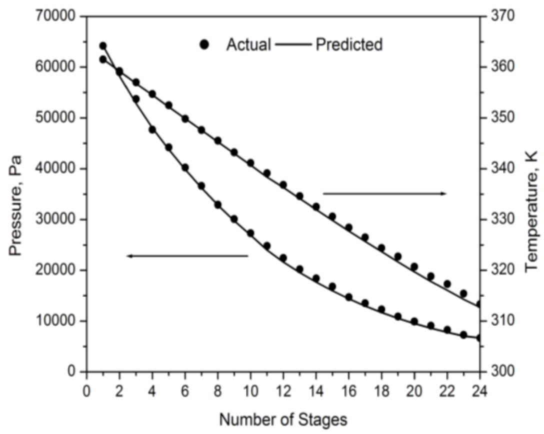



*Figure 3: Pressure and brine temperature profile*

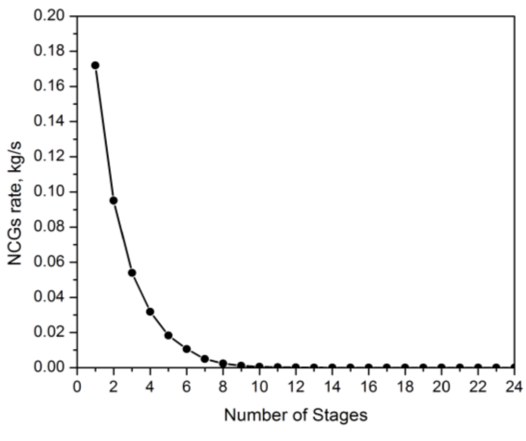



*Figure 4: NCGs release per stage*

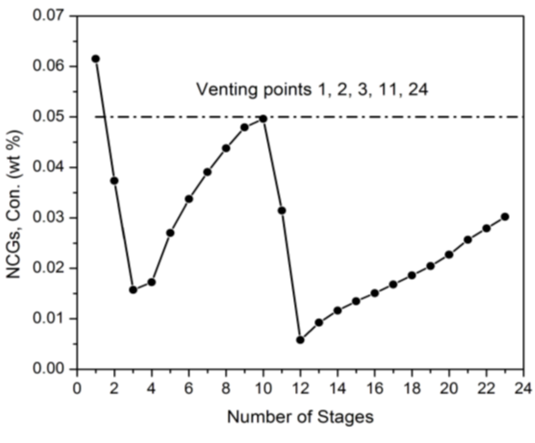



*Figure 5: Venting in the first three stages*

<u>*CASE 1:*</u> Here, the venting point is installed in the 2nd stage as shown in Figure 5 and Figure 6, then two more venting points, wherever they are installed, are required to keep the NCGs less than 0.05, five venting points in total. In Figure 5, the third and fourth venting points are installed in the 3rd and 11th stages. In Figure 6, on the other hand, the third and fourth venting points are installed in the 6th and 21st

stages. However, the difference between the two figures is the performance ratio (PR) which is 7.74 kg product per kg steam in the former and 7.86 in the latter.

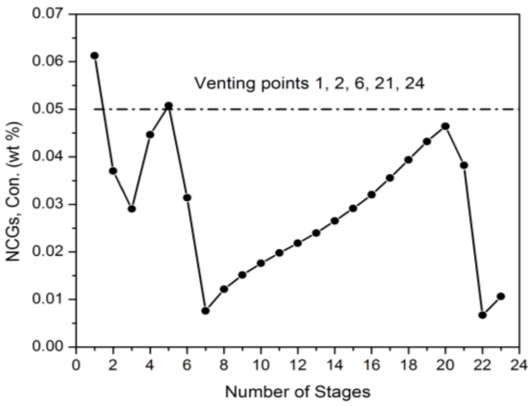



Figure 6: Venting in different stages (Five points)

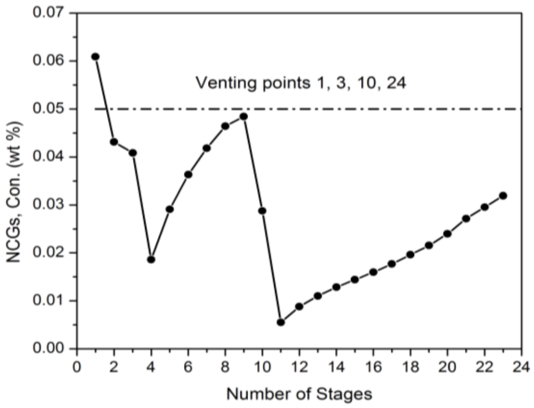



Figure 7: Venting in only four stages

CASE 2: Here, the venting point is installed in the 3rd stage instead of the 2nd stage, then only one extra venting point is required to keep NCGs under control as shown in Figure 7. Having less number of installed venting points, the PR is slightly improved to be 7.9 due to the less vapour escaped through venting system. This will also reduce the capital investment.

**4.2 Effect of NCGs on overall heat transfer coefficient (OHTC)**

Alasfour and Abdulrahim (2009) and Said and Mujtaba (2010) obtained similar pattern of OHTC due to their fixed value of NCGs concentration in every stage. Alasfour and Abdulrahim (2009) used 0.04 in every stage and Said and Mujtaba (2010) used different value up to 0.06 but constant in every stage. The OHTC correlation they used (El-Dessouky and Ettouney, 2002) shows that the OHTC is affected only if the NCGs concentration exceeds 0.05 as shown in Figure 8. Here, the venting points location are more relaxed to allow the concentration of NCGs to reach 0.055 to show clearly the effect of these gases on the OHTC. Different cases are studied and the results are plotted in Figure 8.

*CASE 1*: When venting points are installed in the 1st, 2nd, 7th and in the last stage, the OHTC drops in the 5th and 6th stages to 2.88 kW/m$^2$ $^oC$ and 2.76 kW/m$^2$ $^oC$ respectively due to the increase of the NCGs concentration to 0.055 and 0.056 respectively. Thus, venting point is required to vent NCGS and as result the OHTC increased to the normal value. Also, OHTC is affected in the first stage and second stage in the rejection section due to the increase of NCGs concentration in these stages.

*CASE 2:* When the venting points are installed in the 1st, 2nd, 3rd, 12th and in the last stage or 1st, 3rd, 11th and in the last stage, the OHTC will only decrease to 2.81 kW/m$^2$ $^oC$ in stage 10 where the concentration of NCGs reaches to 0.053.

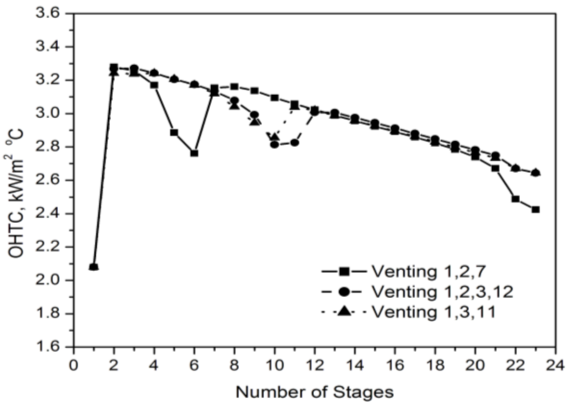



Figure 8: Overall heat transfer coefficient profile

It is important to mention that in all cases the concentration of the NCGs in the first stage is around 0.06 due to high release of the NCGs. At this concentration, the OHTC is found to be as low as 2.08 $kW/m^2\,^oC$ compared to 3.26 $kW/m^2\,^oC$ in the second stage.

## 5. Conclusions

In this research, a dynamic model is presented for MSF desalination plant using gPROMS modelling tool. The model is used to study the effect of the venting points on the performance of MSF plants and also it is used to study the effect of NCGs on the OHTC. The model predictions are validated against the actual data and a good agreement is obtained. The gases dissolved in the sea water are mostly liberated with the vapour produced in the first stage and thus venting in the first stage is essential. In order to avoid high NCGs concentration in the downstream stages, vents are taken from the second or third stage. Additional venting points are provided at intermediate stages and at the final stage. The location of venting points is very important and plays an essential role in designing MSF plants. Based on the simulation results, it was found out that venting point installed in the third stage rather than in the second is very important and more efficient in term of reducing energy losses and increase performance ratio.

Similar to Said and Mujtaba (2010), the effect of NCGs on the OHTC was clearly noted especially if the concentration of the NCGs exceeds 0.05 (wt. %). It was found out that at 0.055 (wt. %), the OHTC is reduced by 12 % as it can be seen in the fifth stage in Figure 8 and up to 37.5 % if the concentration of NCGs reaches 0.06 (wt. %) when the OHTC drops to as low as 2.08 $kW/m^2\,^oC$ in the first stage. Thus, for better performance it is required to keep the NCGs concentration to less than 0.05 (wt. %). NCGs less than 0.05 affect heavily the vapour side heat transfer coefficient but due to the fouling resistance, this effect is nearly negligible when it comes to the OHTC.

The results may become different if the release of NCGs due to chemical reaction is considered. Therefore, further study including the release of NCGs due to chemical reaction is under investigations.

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