Effect of Scaling on Design and Operation of Thermal Seawater Desalination Plants

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1. Introduction

Scaling of heat transfer and evaporation surfaces has different effects on the design and operation of evaporators and related heat transfer equipment. The process and design engineers have to consider that scaling reduces effectiveness (production and/or heat consumption) of the process. As in many cases the supplier has to guarantee that within a certain operation period the full production is maintained and consumption figures are not exceeded, scale formation – as far as not completely avoidable by other measures – will require over-sizing of the evaporation/heat transfer surfaces, thus creating significant increase of investment cost.

In this presentation the different ways how scaling affects the main thermal evaporation processes will be explained:

MED = **M**ulti-**E**ffect **D**istillation
MED-MVC = **MED**, driven by means of **M**echanical **V**apour **C**ompression
MED-TVC = **MED**, driven by means of **T**hermal **V**apour **C**ompression
MSF (**M**ulti **S**tage **F**lash), as Once-Through or Brine Recirculation Process

For better comparison all curves in this presentation shown for the a. m. processes have been computed on the basis of plants with the same thermal efficiency (324 kJ/kg).

As one of SERCK COMO's main business is the marine sector, some information will be given about the problems with scaling in ship evaporators.

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2. Scaling in MSF Evaporators

2.1 MSF Working Principle

The main characteristic of the MSF process is that heat transfer to the seawater or brine and the evaporation procedure itself take place separately. In a flash evaporator (Fig. 1 and Fig. 2) the seawater/brine is heated up to a certain top temperature

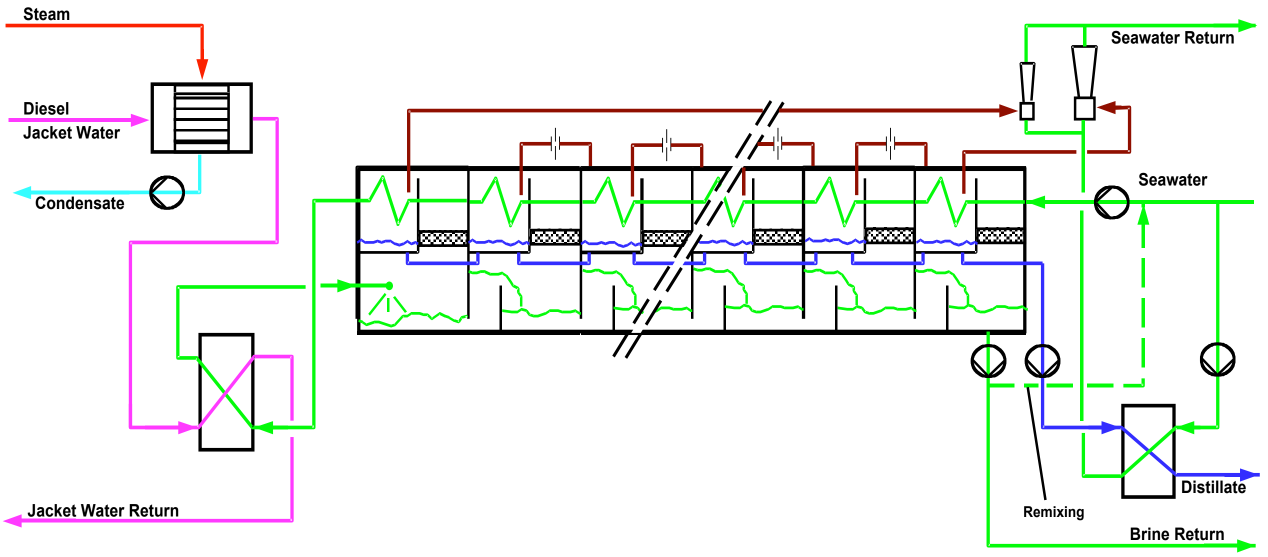

Fig. 1: MSF Once-Through Plant for heat Supply from Diesel Engine

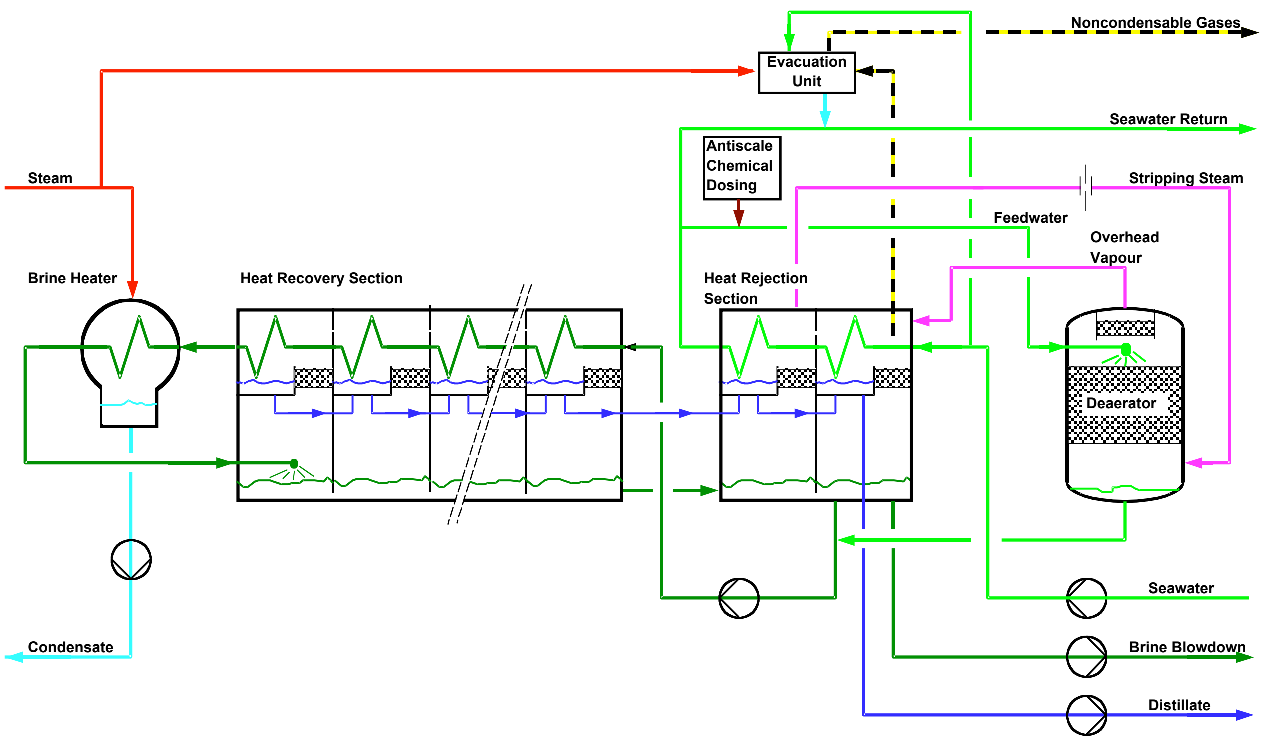

Fig. 2: MSF Plant with Brine Recirculation

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(BTT = between 88°C and 118 °C according to the design philosophy of the plant). This heating procedure takes place under pressure, boiling during heat transfer is strictly avoided. As thus the velocity of thermal distortion of the bicarbonates is minimized, scaling is reduced to a minimum, but it still takes place. Velocity of precipitation of calcium Carbonate is an exponential function of the temperature. A more conservative design applies a low brine top temperature. Once through evaporators – due to the fact of a very low concentration factor of the seawater (cf < 1.1) – are less sensitive than MSF evaporators with brine recirculation (cf=1.5 – 2). In addition, The brine recirculation plants may suffer from Magnesium-Hydroxide scales, caused by the effect of pH-rise in recirculation brine.

2.2 Consideration of Scaling in MSF Evaporator Design

In many cases the customer specifies a minimum operating period between chemical cleanings of the plant or he requests to design the condenser surfaces for a certain fouling factor (FF). FF is often – as in this presentation – called a factor, although having the inverse dimensions of the heat transfer coefficient (OHTC): m^2K/W.

The optimisation of a MSF plant to be designed for a certain capacity and thermal efficiency takes place by "playing" with the following main design parameters:

- Tube length
- Tube diameter
- Number of tubes
- Number of stages

The brine top temperature, the max seawater temperature and the selected process (recirculation or once-through) affect this design as well, and – of course – the fouling factor "FF". How FF influences the design of once-through evaporators is shown by a typical example:

The first possibility for installing reserve surface is to lengthen the condenser tubes (Fig.3). The application of this method only leads soon to a very wide and short evaporator vessel with unfavourable proporations. (in units with smaller capacities the condensers can have more than 1 pass in order to reduce tube length, not considered here).

The second possibility is to reduce the tube diameter. As in many cases – with respect to the possibilities of a mechanical cleaning – minimum tube diameters are specified, there is in most cases not much room to play with this parameter and for this reason this is not considered here.

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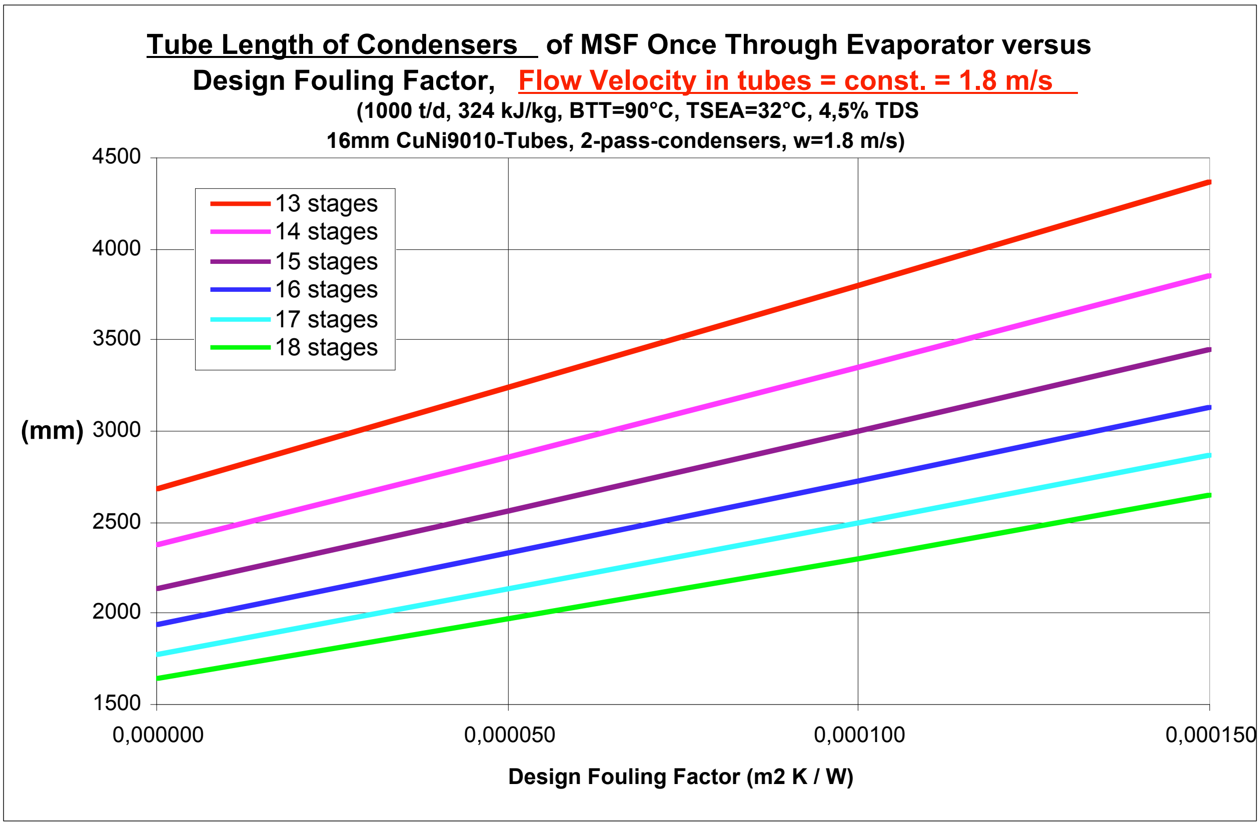

Fig. 3: Influence of Design-FF on the Tube Length

The third possibility is to add additional tubes in the condenser. This will soon lead to uneconomically low flow velocities (Fig. 4) in the condenser tubes. The drop of

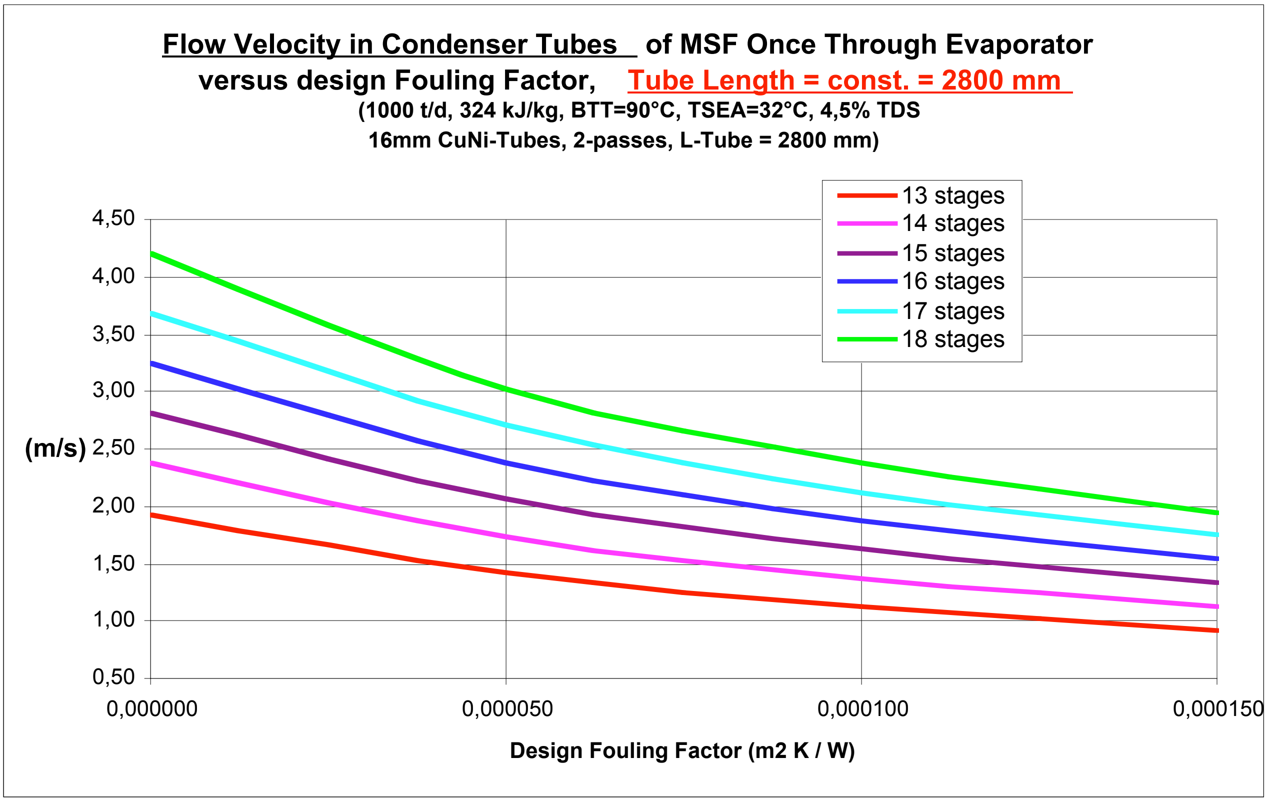

Fig. 4: Influence of Design-FF on Velocity in Tubes (l-tube=const.)

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velocity is accelerated by the decreasing heat transfer coefficients in the tubes, resulting in an over-proportional increase of number of tubes.

The most common method for consideration of tube fouling/scaling is to add stages. It should always be always tried to use standardised stage geometries in order to minimise design and manufacturing cost. The typical result of such an optimisation is shown in Fig. 5a/b. Tube length is constant, the fine adjustment of the thermal efficiency takes place by varying the number of tubes. The flow velocities are thus varying within the range acceptable for the selected CuNi-tubes.

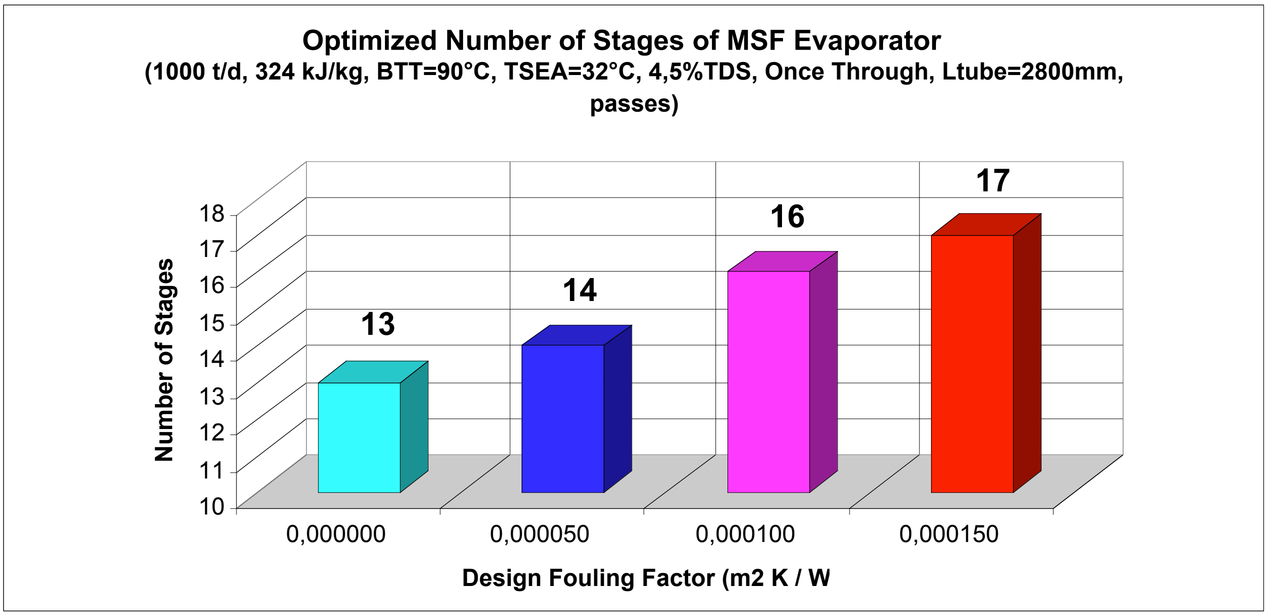

Fig. 5a: Optimisation of Number of MSF-Stages

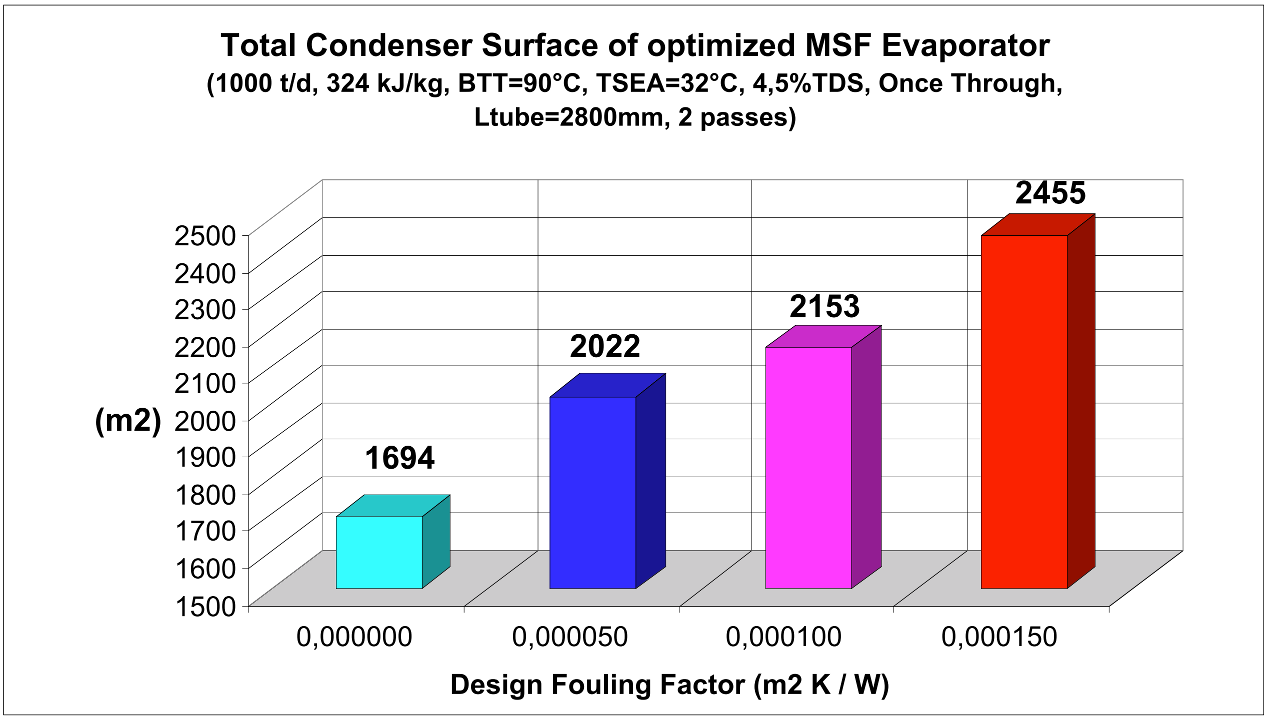

Fig. 5b: Flow Velocities in Tubes of optimised MSF Evaporator

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In this example of a Once-Through MSF Evaporator (design data given in the diagrams) we have to increase the number of identical stages from 13 (no fouling allowance considered) to 17 (for FF = =.000150 m^2 K / W). The cost portion of the evaporator in a complete unit may be approx. 60 %, cost increase of total MSF-unit due to consideration of fouling will be – correspondingly - approx. 18 %.

2.3 Effect of Scaling/Fouling on Operation of MSF Evaporators

How does such an over-dimensioned evaporator behave in operation? As the water production in an MSF evaporator is proportional to the flashing seawater/brine flow and the flash temperature range, the influence of tube scaling/fouling on the water production is principally negligible. As the LMTD in the condensers forms part of the temperature rise in the brine heater, the heat consumption dependes strogly on the fouling of the tubes. This effect is shown in Fig. 6. A flash evaporator with given

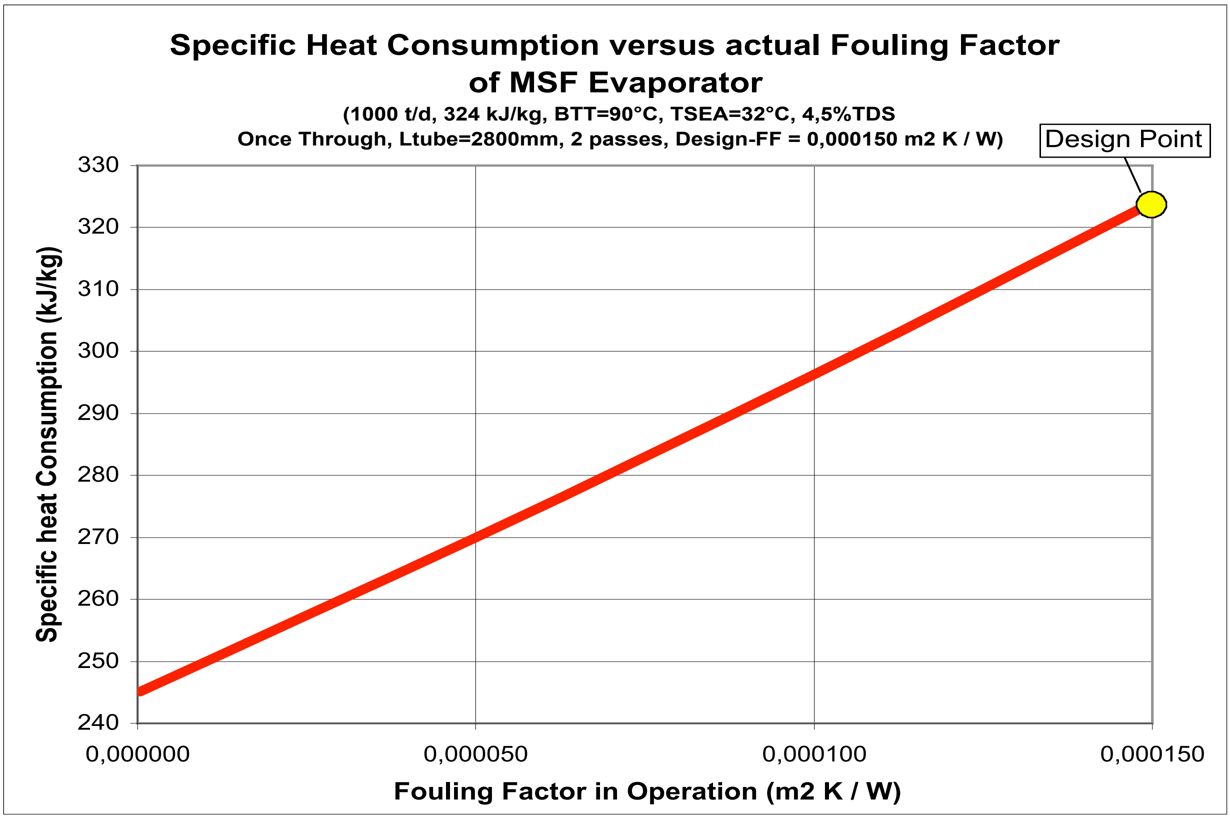

Fig. 6: Influence of actual Fouling Factor on Heat Consumption

data, designed for FF=0.000150 m2 K / W should have – when being clean – a heat consumption of 75% of design value only. The author has the experience that such energy savings in clean evaporators are not always found during commissioning although they should. It seems that very often the fouling allowance is partially "consumed" by temperature losses on the condensation side due to partial pressure of CO_2 in the condensers, caused by an improper design of the gas extraction zones. An intelligent customer should request in the tender specification for a performance test of the clean evaporator for verification of the design-FF.

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3. MED-Evaporators

3.1 HTE-Working Principle

Most of the existing MED-Evaporators for seawater desalination apply the HTE-Principle as shown in Fig. 7. A distribution system (not necessarily using spray nozzles as shown), distributes the feed water on top of the horizontal tube bundle. The feed water flows from tube row to tube row and partially evaporates. A typical feed water/distillate ratio is 3 : 1, which means that 33.3% of the feed water are evaporat-

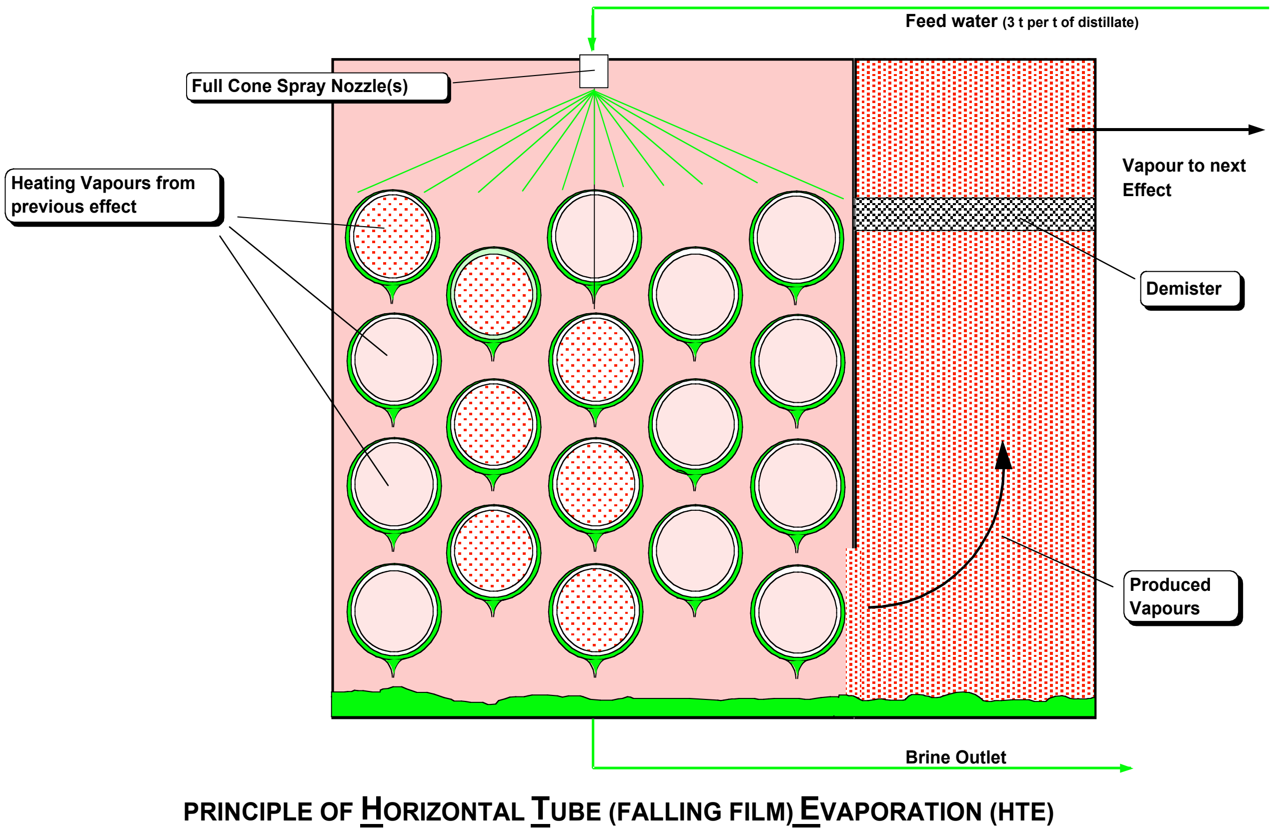

Fig. 7: Working Principle of Horizontal Tube (Falling Film) Evaporator

ing. The main problem in designing such evaporators is to ensure a sufficient flow of feed water on the tubes (given as kg / s / m tube length). A practical low limit known to the author is 0.032 kg/s/m for 24mm tubes (such figures are of course subject to individual experience of the different suppliers). It is good to have many tubes in the vertical direction because this keeps the flow per tube high. This means that for an evaporator of small capacity it is more difficult to maintain sufficient wetting of tubes than for a plant with a high capacity.

A high thermal efficiency requires higher evaporation surfaces, which means that – with respect to the scaling risk - it is easier to design an evaporator with low thermal efficiency. When considering design fouling allowances the dilemma is that adding of tube surface lowers the feed water flow per tube and thus automatically increases

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the risk of scaling. An increase of the feed water flow – the first idea to overcome the problem - is no solution. As the feed water is more or less sub-cooled in comparison to the evaporation temperature in the effect, an increase of the feed water injection would increase the heat loss for preheating of the feed-water as well as the product loss due to a direct condensation taking place at the sub-cooled injected feed water. The result of increased feed water injection would be: the thermal efficiency of the whole evaporator would drop, or in a TVC-driven MED plant again additional surface would become necessary for maintaining the desired plant efficiency: a real vicious circle!

3.2 Effect of Scaling on the design of an MED-Evaporators

Fig. 8 is the flow diagram of a 4-Effect MED evaporator with feed water preheaters, directly heated by steam. Fig. 9a shows the influence of the design fouling factor on the evaporation surface to be installed for a 8-effect plant. Consequently the feed wa-

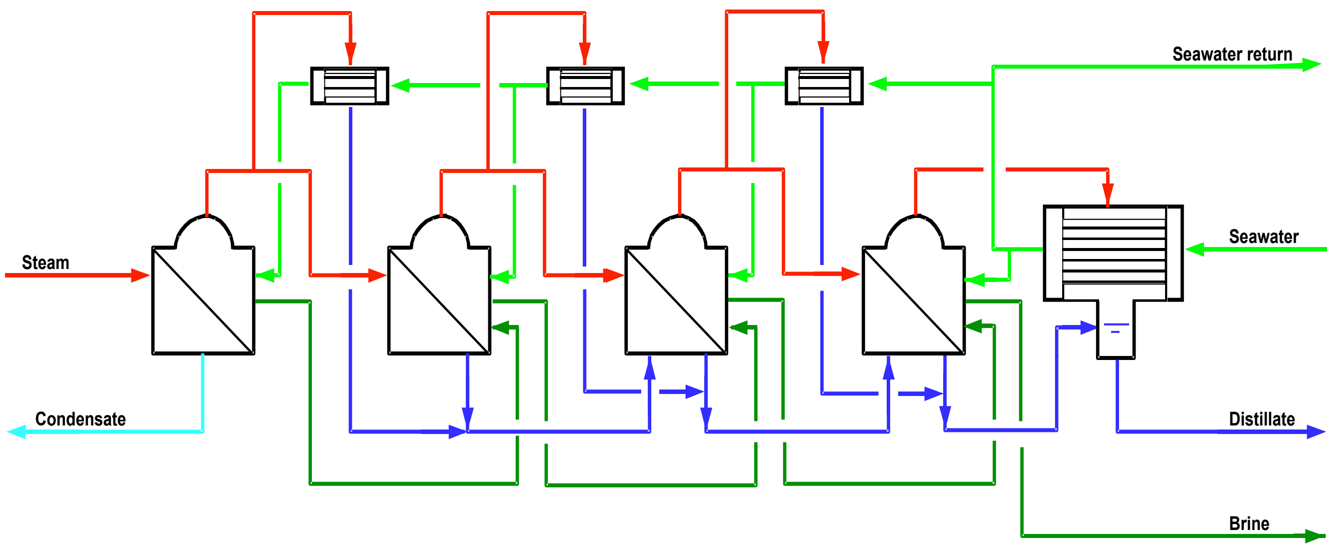

Fig. 8: Simplified Flow Diagram of MED Evaporator with Feed Water Pre-Heaters

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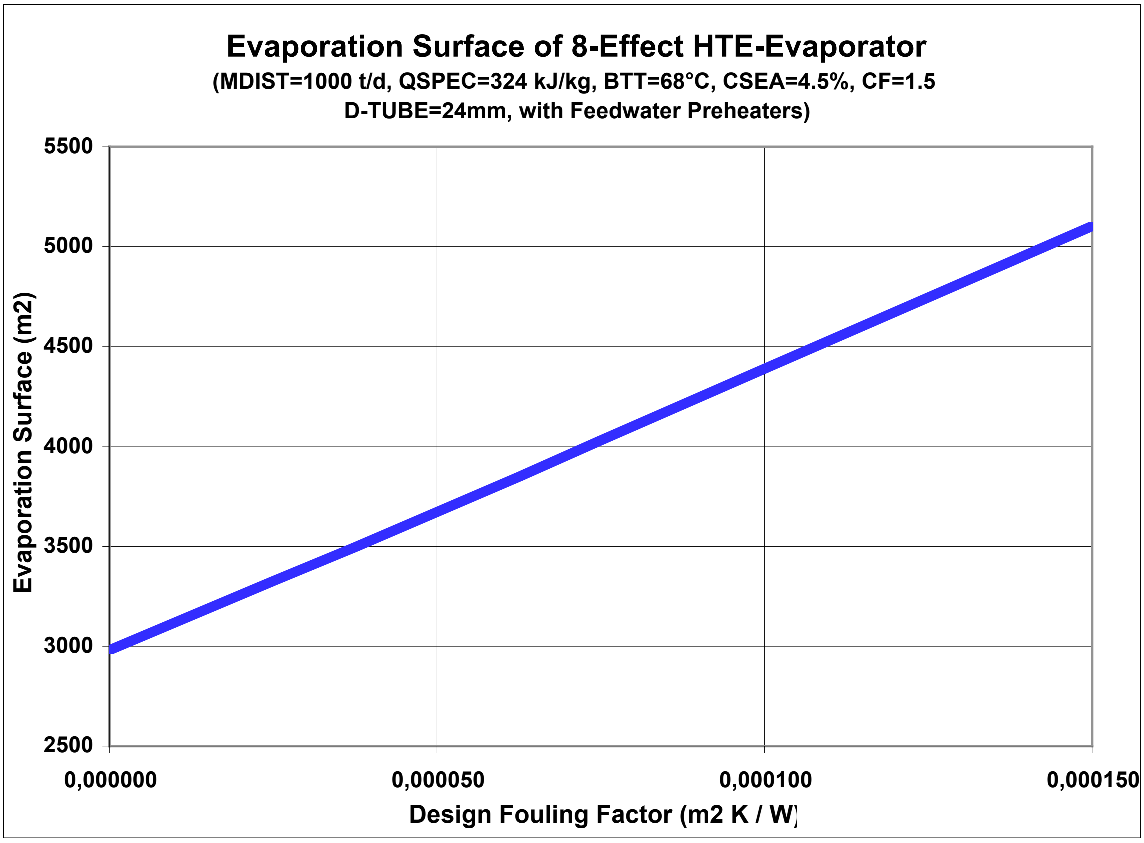

Fig. 9a: Evaporation Surface of 8-Effect THE-Evaporator

ter flow per meter tube length is dropping with the design-FF (Fig.9b). For this rough calculation is was assumed that the length-height-width ratio of the tube bundles is

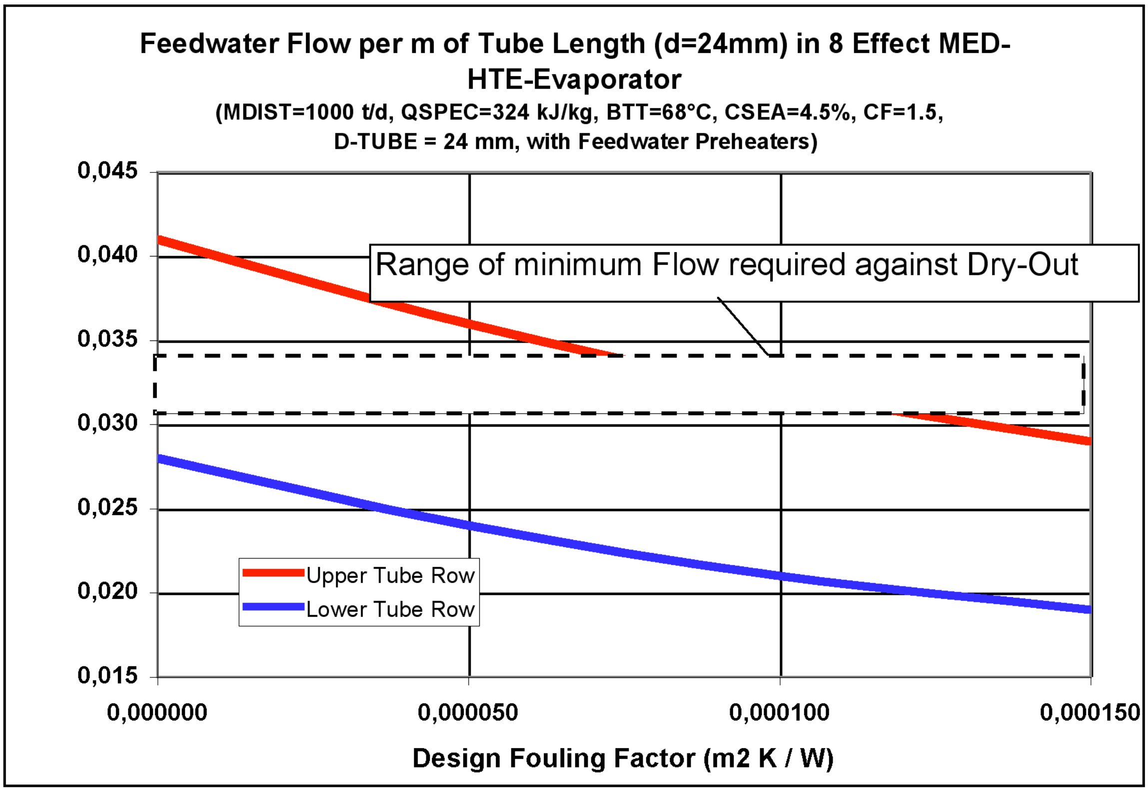

Fig. 9b: Feedwater Flow per m of Tube Length (d=24mm) in 8-Effect HTE-Evaporator

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4:2:1. As thus the top area of the tube bundles grows proportionally to the evaporation surface with an exponent of 0.66, the feed water flow per tube drops correspondingly. In this example the consideration of the design fouling factors leads to a specific feed water flow below the allowable limit, so that another tube bundle geometry than given above has to be selected (bundle to be higher and more slim).

3.3 Increase of Feed water Flow

The first idea for enabling better wetting of tubes is to increase the feed water flow per effect. Fig. 10 shows that this is not a very recommendable solution. The disadvantageous effect of the sub-cooled feed water injection creates a significant increase of heat consumption with declining design concentration factor and correspondingly higher feed water injection rates.

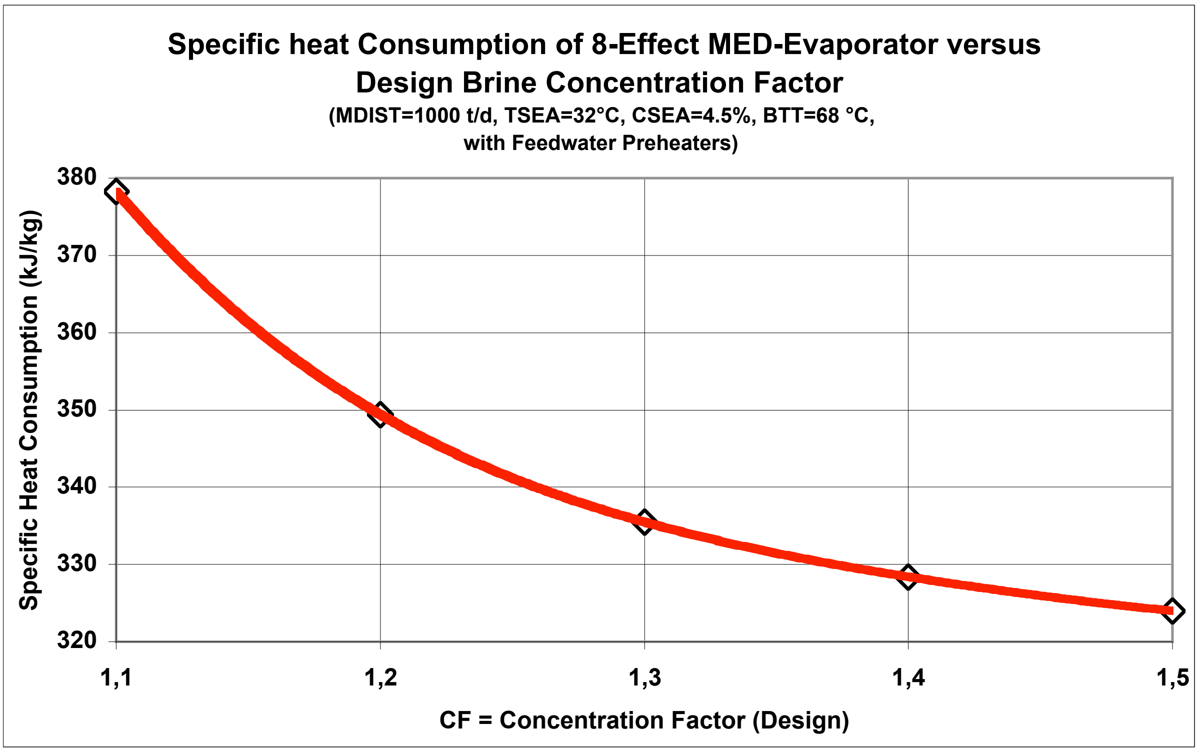

Fig. 10: Effect of Design-CF on heat Consumption of 8-Effect MED

3.4 Effect of Scaling on the Operation of an MED Evaporator

As to be seen in Fig. 11a, fouling/scaling of MED evaporation surfaces does not affect the thermal efficiency very much. There is a slight increase of heat consumption with rising FF due to the fact that the temperatures in the effects rise more quickly than the feedwater temperatures at inlet of effects. This results in higher heat and product losses in the effects.

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Fig. 11b shows the increase of the brine top temperature in effect 1 while maintaining the water production in spite of scaling/flowling of the evaporation tubes. In cases where the temperature at the hot end of the plant can not be increased any more (due to the limited temperature level of the heating source), further scaling leads to a reduction of production (not shown in the diagram). This has f. i. to be considered when operating such a plant with motor water from a Diesel engine.

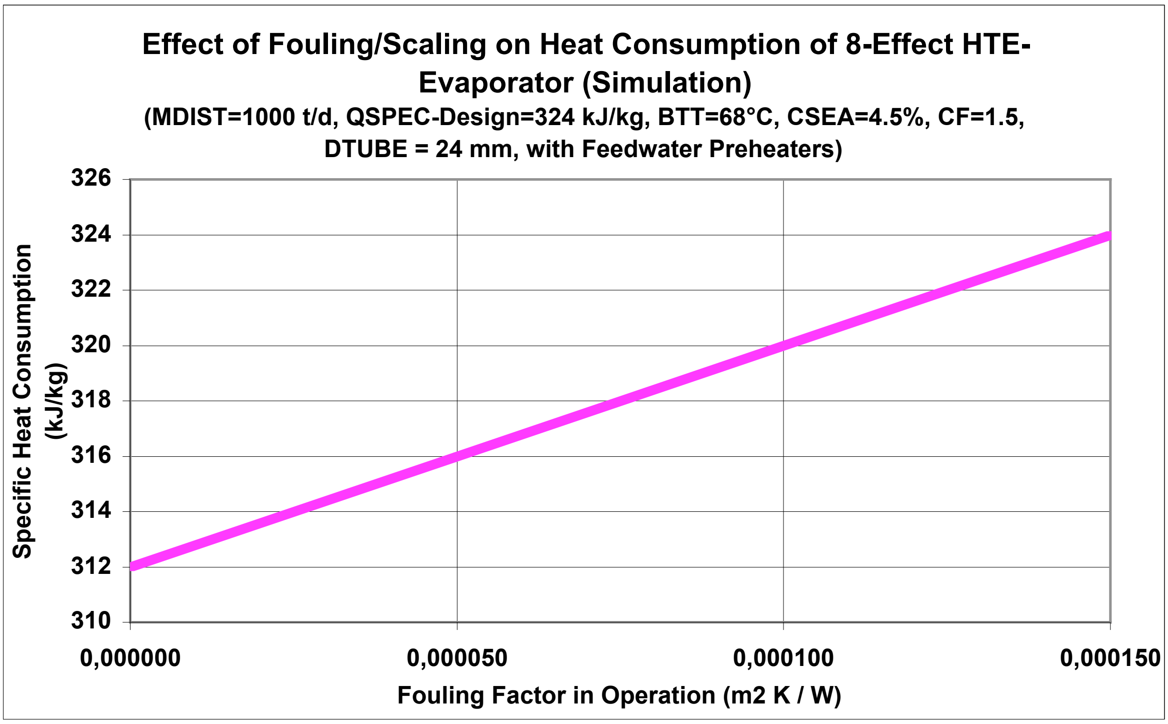

Fig. 11a: Effect of Scaling on Heat Consumption in MED-Plant

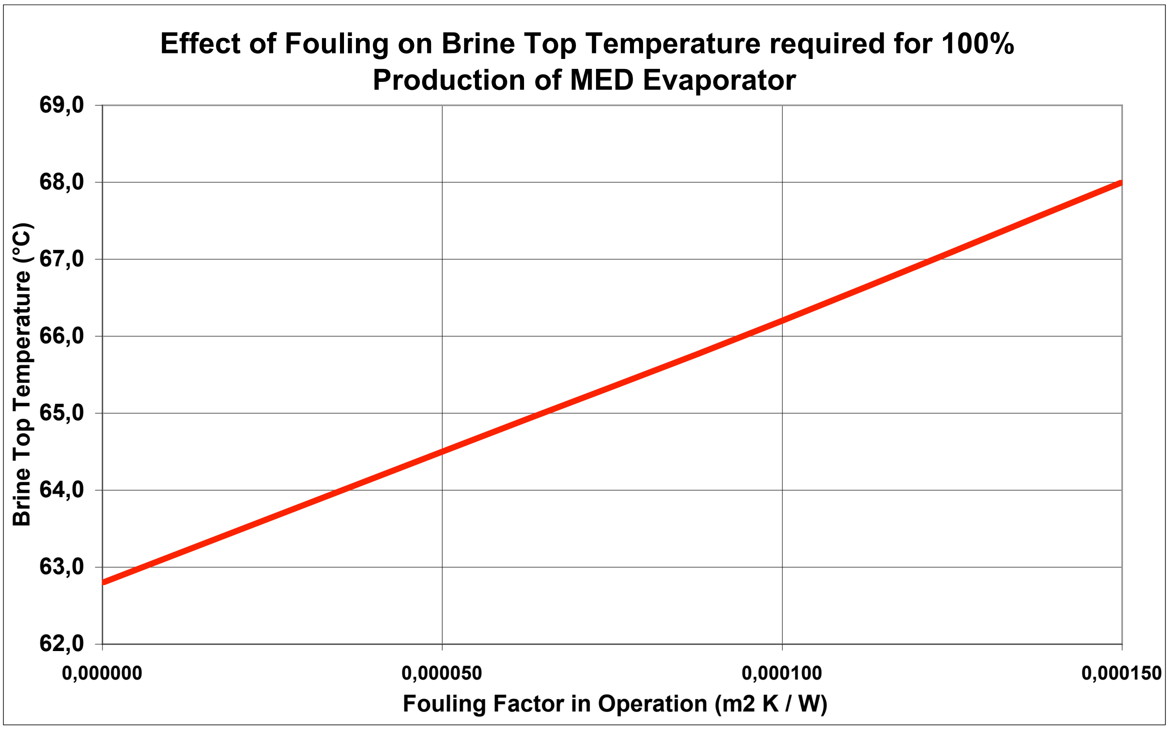

Fig. 11b: Effect of Scaling on Brine Top Temperature in MED-Plant

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4. MED-TVC

Fig. 12 is the flow diagram of a single effect HTE-Evaporator with thermal vapour compression. Due to the application of the vapour recompression, such

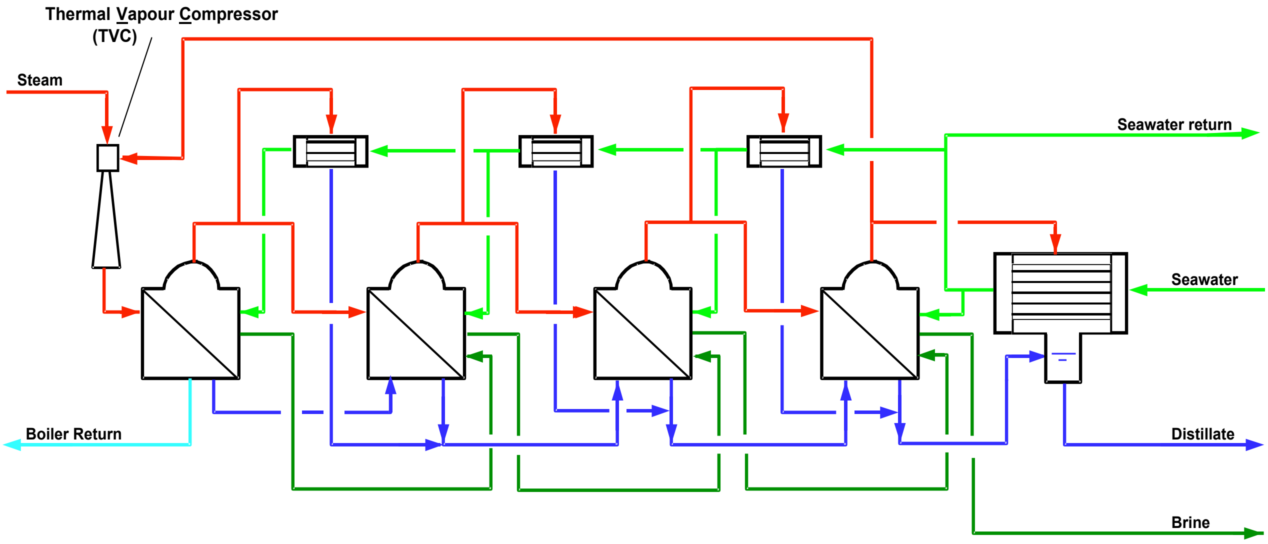

Fig. 12: Flow Diagram of Single-Effect THE-TVC Evaporator

an evaporator has the same thermal efficiency as a directly heated MED evaporator, having the 2-2.5-fold number of effects and much more evaporation surface. Figure 13a shows the required evaporation surface versus the design fouling factor.

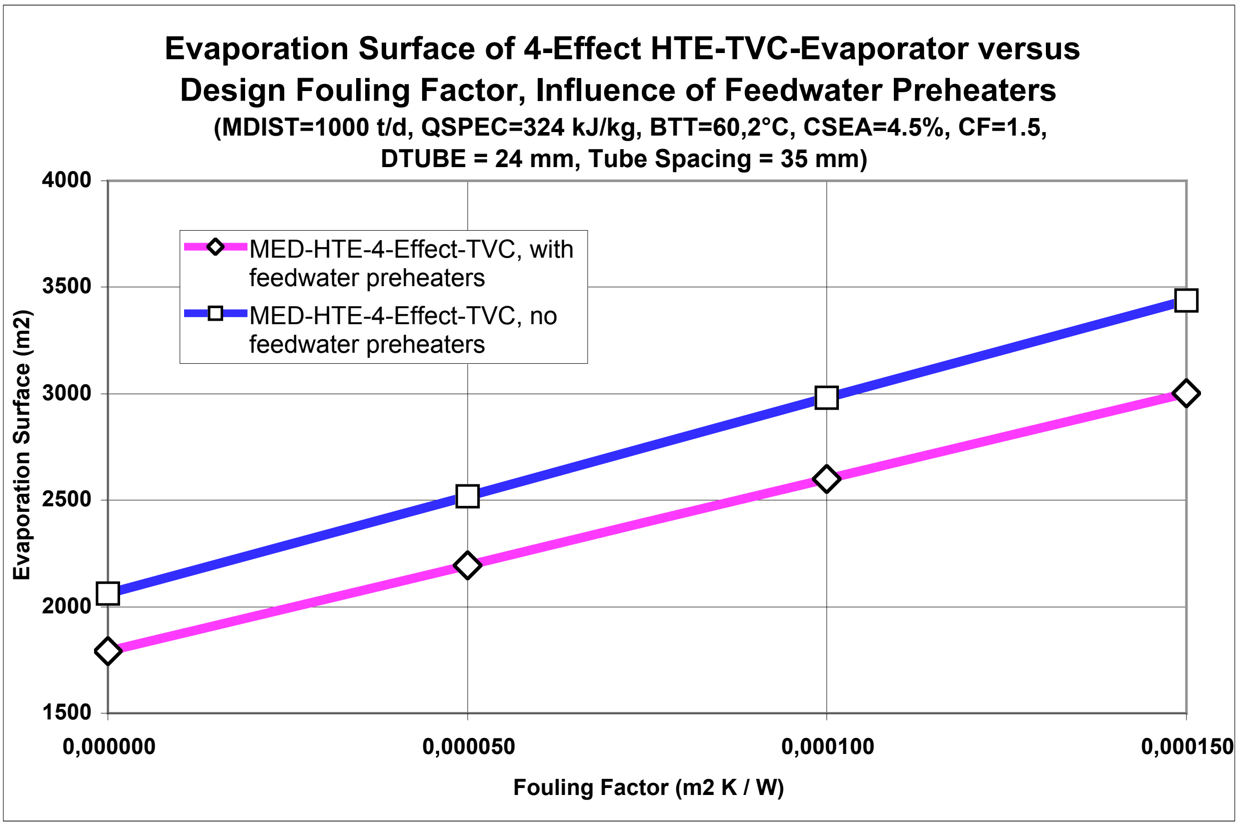

Fig. 13a: Effect of Design Fouling Factor on Evaporation Surface of w-Effect MED-HTE-TVC-Evaporator

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The evaporation surfaces are significantly smaller than in the 8-Effect MED-plant - approx. 60% with and 70% without feed water pre-heaters, at the same thermal efficiency. With respect to the scaling risk it is better to equip such a TVC evaporator with feed water pre-heaters because this reduces the evaporation surfaces by approx. 13% and thus the problems of feed water distribution significantly. The specific feed water flow (Fig. 13b) remains – even at full design fouling factor – above the critical limit. This means that – when applying the thermal vapour com pression - it is easier

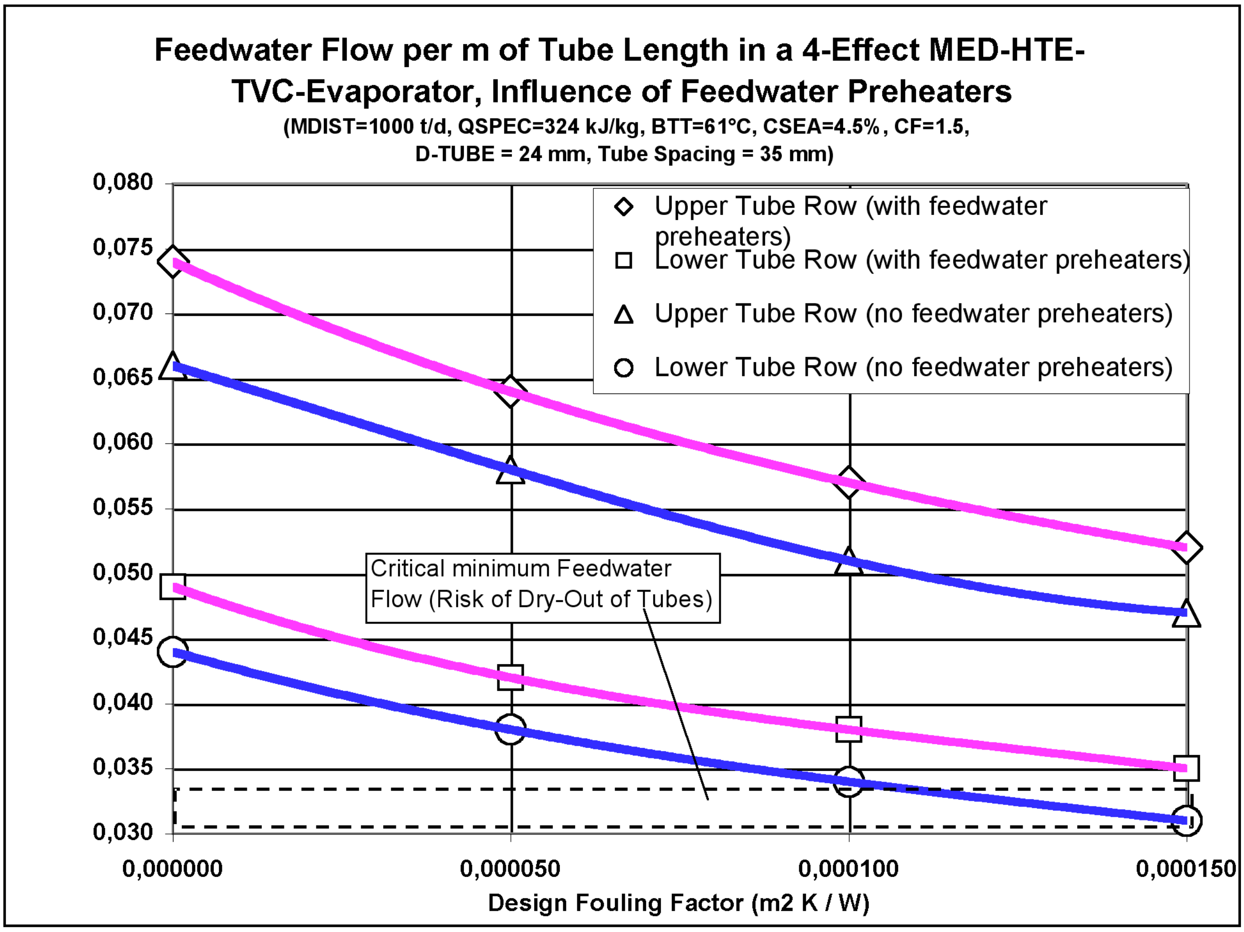

Fig. 13b: Effect of design Fouling Factor on Feedwater Flow on Evaporator Tubes

to maintain sufficient feed water flows on the tubes than in a comparable directly heated MED evaporator.

A special risk arises from the operating characteristics of the thermal vapour compressor. Fig. 14 is a typical pressure characteristic curve of a Thermo-Ejector. A 4-Effect MED-Evaporator designed for a heat consumption of 324 kJ/kg, operated with 10 bar steam, will have a design temperature difference between effect 1 and effect 4 of approx. 20 K, where a thermo compressor can recompress approx. 1 t of vapour per 1 t of motive steam. In clean condition, the delta-t between effect 1 and 4 will drop to approx. 15K, without change in the suction flow of the ejector. In case of exceeding the design fouling factor in operation, the suction flow will sharply drop and may even become instable, creating a corresponding drop and fluctuations of water

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production. This means that in a TVC-driven evaporator it is still more important to install sufficient fouling allowances than in a directly heated MED evaporator. ON the other hand the required surfaces are smaller than in a directly heated MED plant.

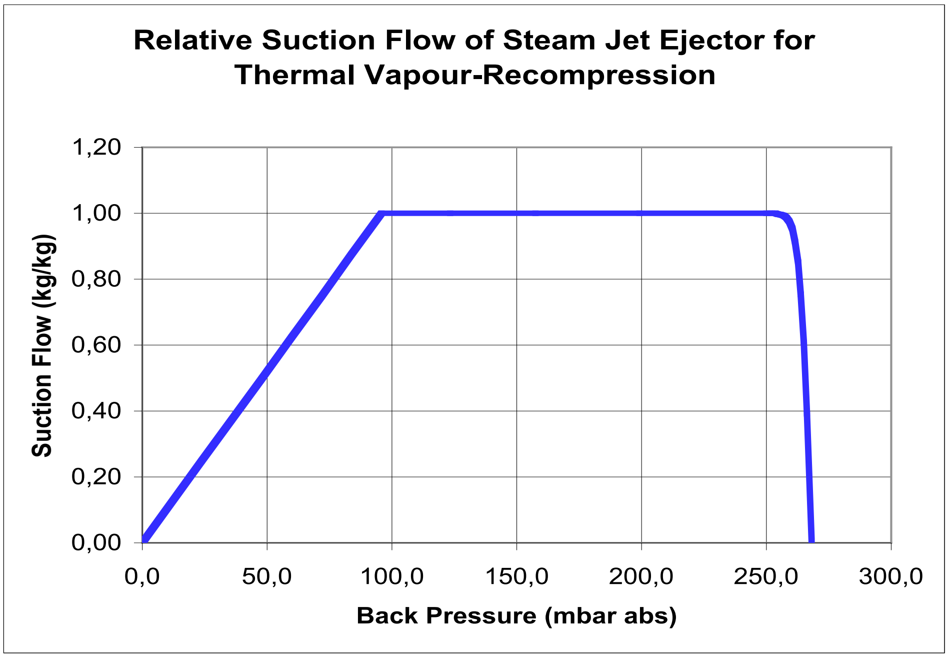

Fig. 14: Typical Pressure Characteristics of a Thermo-Compressor

An increase of feed water flow (= reduction of concentration factor cf) is not such a problem as well (Fig. 15). Especially when using feed water pre-heaters, the additionally required evaporation surface for maintaining the specific heat consumption is acceptable.

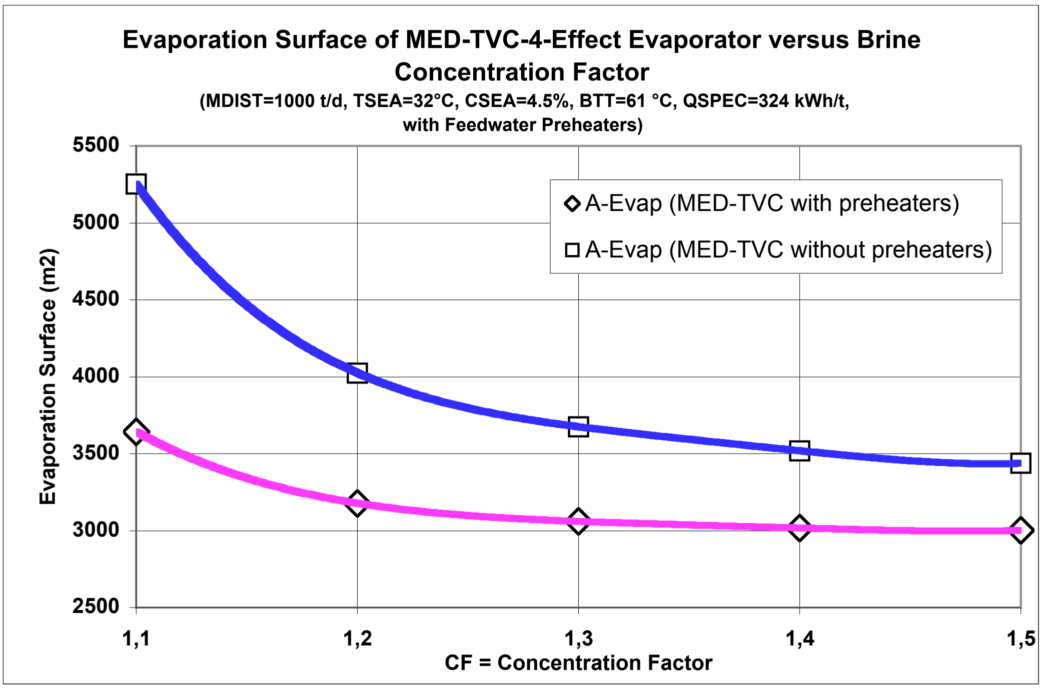

Fig. 15: Effect of Design-CF and the presence of Feed Water Pre-Heaters on Evaporation Surfaces in a TVC-THE-Evaporator

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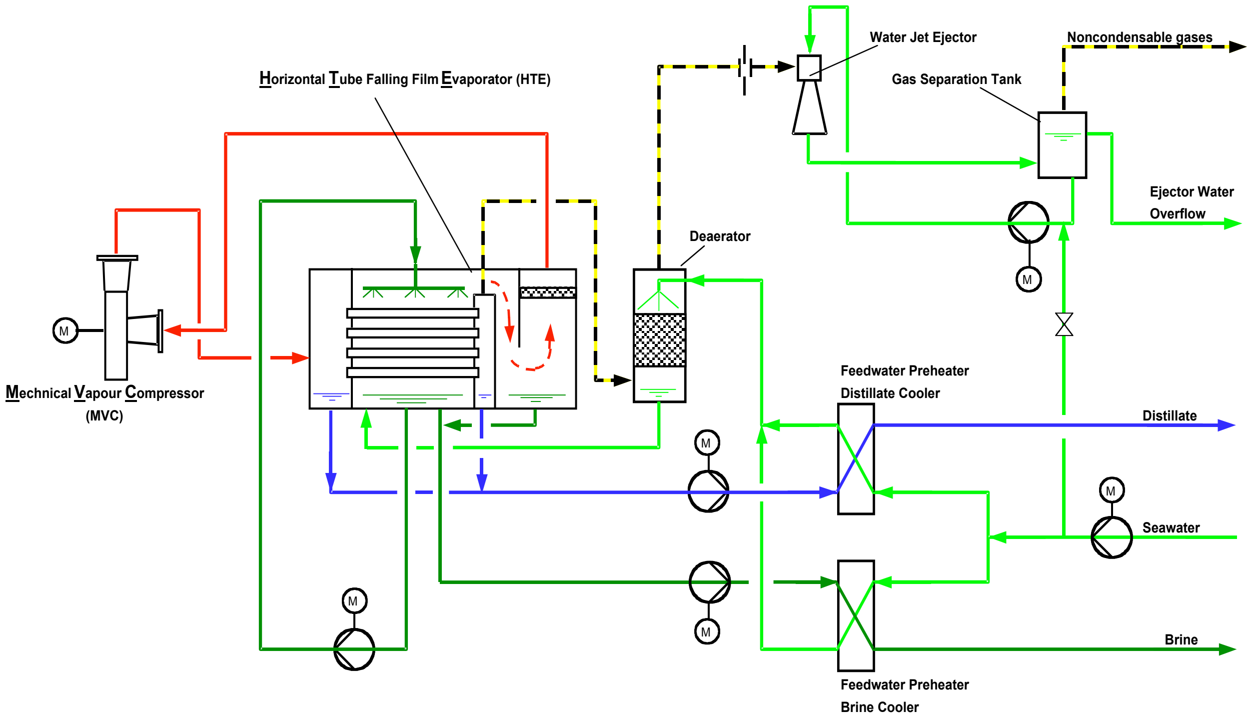
5. MVC-HTE Evaporators

Fig. 16 is the typical flow diagram of a MVC-driven evaporator with horizontal tubes. A sufficient supply of the tubes with feed water is not a problem in such



MVC-HTE-Evaporator (Horizontal Tube Evaporator with Mechanical Vapour Compression)

Fig. 16: Flow Diagram of MVC-THE-Evaporator

plants because this is only a matter of sufficient capacity of the brine recirculation pump. The 2 feed water pre-heaters serve for heating the feed-water up to the temperature required to close the heat balance of the evaporator which – typically – operates at an evaporation temperature of 60 – 65 °C. The vapour fan typically creates a rise of the vapour saturation temperature of 5 – 5.5 K. After subtraction of temperature losses due to vapour transportation and the boiling point elevation – a net delta-t for heat transfer of approx. 3.0 K is available.

The required reserve evaporation surfaces are in the same order of magnitude as in the described MED evaporators. More interesting is the behaviour in operation. Fig. 17 shows the typical characteristic (as saturation temperature rise) of a vapour compressor, together with the characteristic of the evaporator for 3 different degrees of fouling, assuming a constant evaporation temperature. As soon as the design fouling factor is exceeded, the water production will drop below design. As long as fouling/scaling is below design, the plant could theoretically produce even more, but practically – with respect to the load of the compressor drive – the compressor speed or the evaporation temperature will be reduced.

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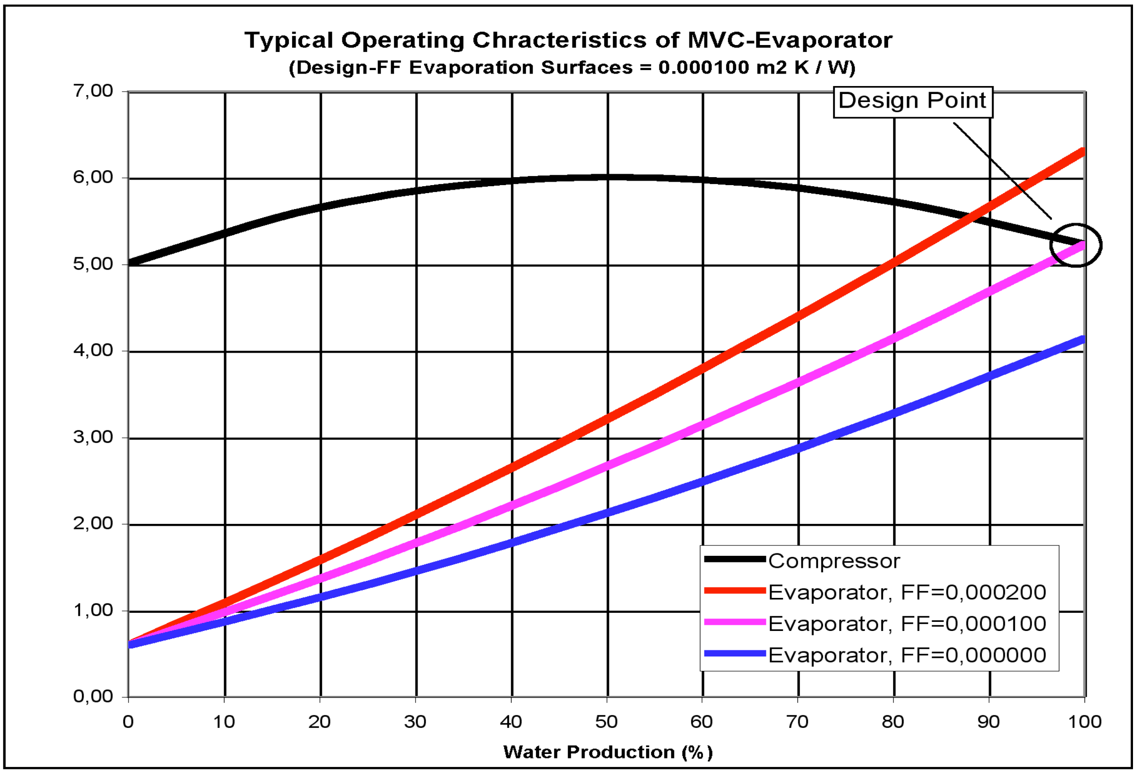

Fig. 17: Influence of Fowling/Scaling on Operation of MVC-Evaporator

An important aspect in a MVC-plant is the energy recovery from brine and distillate for preheating the feed water. Fig. 18 shows what happens if the 2 plate heat exchangers for feed water preheating are fouling. The reduction of heat recovery leads to a drop of the evaporation temperature. As the compressor delivers a – more or less – constant volume flow, the mass flow – which is the water production – declines according to the declining density of the vapour.

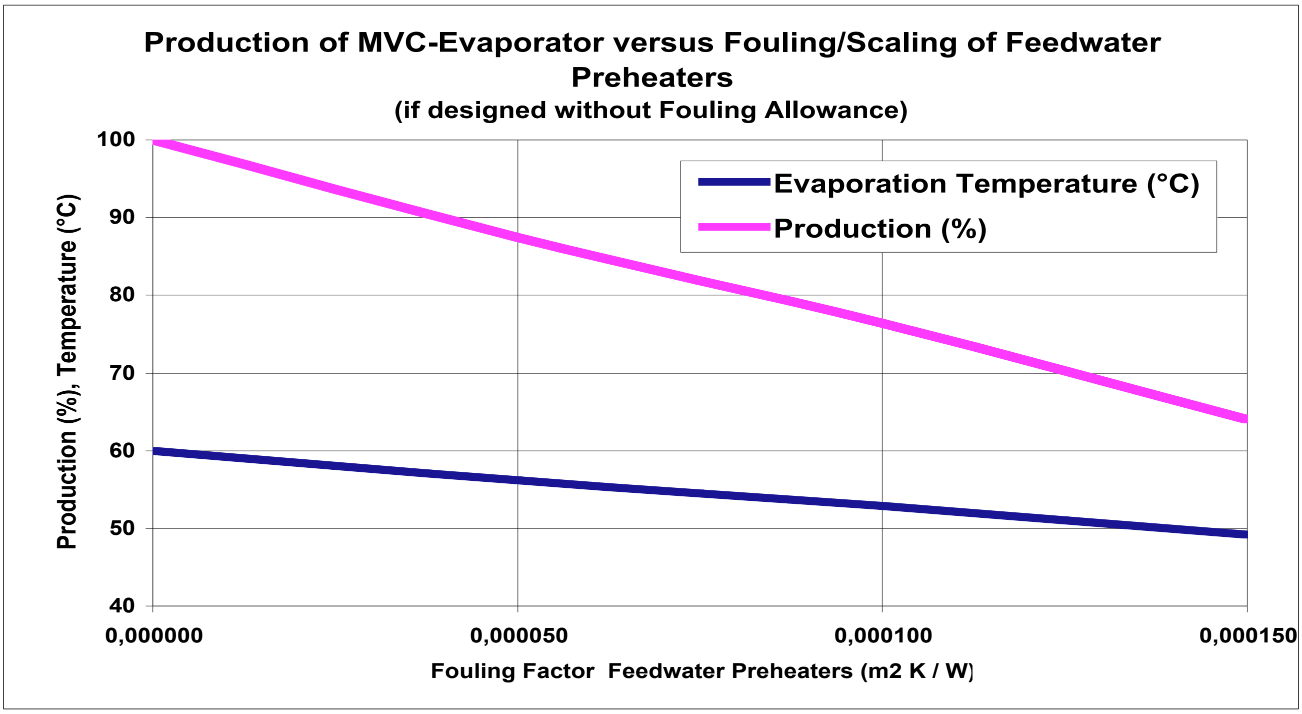

Fig. 18: Effect of Fouling/Scaling of Feed Water Pre-Heaters on Operation of MVC-Evaporator

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6. Scaling in Ship Evaporators

One of SERCK COMO's main business is the delivery of MSF evaporators for cruise ships (a typical flow diagram was shown in fig. 1). As these evaporators are heated with motor water from Diesel engines 85 – 92 °C, the design brine top temperature (BTT) varies typically between 78 and 85 °C. Due to the application of the once-through principle, it is physically impossible to over-concentrate the seawater. The combination of a low BTT, the once-through principle (cf < 1.07) and the very low residence time of the seawater in the evaporator (40 - 60 sec) makes these evaporators very insensitive to scaling. Even low-skilled personnel – as often working in the engine rooms of cruise vessels – is able to operate such evaporators. It was reported that evaporators were operated over weeks without anti-scale chemicals (because it was forgotten to fill the dosing tank or operator wanted to save chemical cost) without drop of efficiency or production. Part load operation without decreasing brine top temperature, at very low flow rates through the condenser tubes, was also reported to be the reason for scaling and fouling.

It was also reported that demisters are scaled, creating pressure and temperature losses and thus reducing the performance of the evaporator. This is a follow of the fact that the vapour spaces in flash evaporators for ships are designed for rather high vapour velocities in order to minimize the requirements for valuable space in the engine room. Besides this no severe problems are arising from the operation of these very simple and reliable once-through flash evaporators.

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