A NEW DESIGN APPROACH TO REDUCE WATER COST IN MSF EVAPORATORS

Authors: E. Ghiazza, P. Peluffo (Fisia Italimpianti)

Presenter: E. Ghiazza

Abstract

Materials and fabrication technologies for MSF evaporators have greatly improved over the last two decades. Titanium is likely to become a valid alternative to the commonly used CuNi or AlBr for heat exchanger tubes, while new materials for evaporators shell and internals are making a debut into the desalination world. Particularly, the use of low-thickness Titanium tubes, allowing high in-tube velocities and low thermal resistance, seems to be likely to turn out well in reducing the size of tube bundles both in terms of heat exchange surface and of cross sectional area. This design solution, together with the use of Duplex stainless steel for evaporators shell and internals could lead to a significant cost reduction for MSF plants. The paper presents a detailed comparison study for a standard MSF evaporator between a classical solution and a possible new design, showing the major technical and economical differences of the two alternatives. Focus is pointed on how this could change our point of view about some “golden rules” for evaporator design. The paper is closed by a cost and benefits analysis of both cases, with some observations about how to minimize the cost of water in order to better meet the world ever-increasing demand of sustainable water supply.
I. INTRODUCTION

In the desalination history, new materials and technologies have been developed and then applied through the years, always improving efficiency and availability of the desalination plants. The use of titanium for the MSF condensers tubes have already been experimented with good result, but nowadays the accessibility of very thin titanium tubes for industrial use gives the designer a number of new possibilities.

Some constraints to titanium application regarding its low thermal conductivity can be overcome, and also the market trend seems to be promising when comparing the cost of titanium with the ones of materials as CuNi or AlBr commonly used for heat exchanger tubes.

The use of Duplex stainless steel instead of clad material for evaporators shell and internals seems to be as well a possible improvement in MSF shell design [1].

II. PROCESS ASPECTS

2.1 Thermal Conductivity

Despite its excellent mechanical characteristics, the use of titanium for MSF condensers tubes has been somewhat discouraged by the low thermal conductivity of this material, when compared with CuNi or AlBr; in fact, due to this reason, the heat exchange surface is higher when using titanium instead of CuNi or AlBr.

However, the wall resistance to heat transfer depends not only on the material thermal conductivity, but on the wall thickness as well, according to the following formula:

\[
\zeta_w = \frac{\sigma_w}{k_{mat}} \quad \text{[kW/m}^2\text{°C]}
\]

where:

- \(\zeta_w\) = wall heat transfer resistance \[m^2\text{°C/kW}\]
- \(\sigma_w\) = wall thickness \[m\]
- \(k_{mat}\) = material thermal conductivity \[kW/m\text{°C}\]

Hence, with the possibility of using tubes of very low thickness, titanium becomes competitive from this point of view with all the other commonly use materials [1], also considering that titanium specific weight is approx. 4.5 kg/dm\(^3\), with respect to 8 ÷ 9 kg/dm\(^3\) for AlBr and CuNi. The lower specific weight reflects into a reduction of the material unit cost when expressed in US$/m^2.
Fig. 1 shows how the thermal resistance for a titanium tube 0.55 mm thick is already lower than for a CuNi 70/30 standard tube 1.0 mm thick, and for a titanium tube 0.35 mm thick is even lower than for a CuNi 90/10 standard tube 1.0 mm thick. Thicknesses down to 0.30 mm are already a reality for titanium tubes.

2.2 Velocity

One of the big advantages of using titanium for condensers tubes is the very high corrosion resistance of this material, but the key issue is that this resistance is not affected by velocity like for CuNi or AlBr (see Fig. 2).

![Figure 2: Corrosion rates for different tubes materials](image)

With CuNi tubes the velocity must be kept not higher than 2.4 ÷ 2.5 m/s, and even not higher than 2.0 ÷ 2.1 m/s for AlBr; this constitutes a limitation to the achievement of a better heat transfer coefficient. On the contrary, the use of titanium allows velocities up to 3.0 m/s and more, yielding a remarkable increase in the heat transfer coefficient (Fig. 3), and consequently to a reduction of the necessary heat transfer surface.

![Figure 3: The influence of velocity on heat transfer coefficient](image)

The second advantage of keeping a higher velocity inside the tubes is the consequent reduction of the cross sectional area of the bundles, leading to a smaller stage dimension. Last but not least, the higher the velocity, the better the flushing of the tubes, assuring a very low deposition rate of scaling, helping to keep the tubes inner surface in clean conditions for longer periods.
2.3 Limits and Constraints

The velocity increase allowed by titanium tubes implies a side effect on the pressure drops of the brine flowing through the bundle. The higher pressure drop (increasing with $v^2$) shall be handled by brine recycle pumps with higher head, and consequently with higher electrical consumption. However, the real limit to the benefits induced by a velocity increase lies in the fact that, using high head brine recycle pumps, the evaporator water boxes and the piping downstream the pumps shall have a higher thickness, being designed on the basis of the pumps shut-off head.

From the tubes materials point of view, titanium tubes offer an excellent corrosion resistance and mechanical characteristics [2]; on the other hand, when inserted in CuNi tube sheets, the problem of galvanic corrosion and hydrogen absorption must be considered for high temperature stages, and a proper cathodic protection must be in any case applied inside water boxes and tube sheets collars. The use of titanium tube sheets to avoid galvanic corrosion is also possible, but then the fixing of the tube sheets to the evaporator walls gets complicated due to the fact that titanium cannot be welded to other materials. Due care must also be taken in considering the increased vibration amplitude shown by low thickness titanium tubes with respect to CuNi or AlBr, and the fact that mandrel machining could be slightly more complicated. At present, titanium tubes are commonly coupled with 70/30 tube sheets, but trials are in progress to use in the future CuNi 90/10 or AlBr tube sheets as well.

2.4 Pro and Cons of Duplex SS

As far as the shell and evaporator internals are concerned, the shrinking and deformations occurring during welding operation should be foreseen somewhat higher for integral or duplex stainless steel than for common cladded material. In addition, a thickness increase using cladded material is relevant only to the non-cladded portion, while for integral or duplex stainless steel this influences the whole material. On the other hand, the use of integral or duplex stainless steel for the evaporator shell and internals allows to avoid the removal (and subsequent restoration) of cladding for all welded joints; another advantage is constituted by the possibility to consider the whole material thickness during structural analysis, and not only the non cladded material thickness.

At last, since less equipment and welding capabilities are necessary to handle integral or duplex rather than cladded material, a wider range of companies is worldwide available, with a positive effect on construction costs due to the higher number of potential competitors.

III. ECONOMICAL ASPECTS

3.1 The Cost of a Single MSF Unit

Roughly speaking, the cost of a single MSF unit is mainly constituted by two items:
1. The evaporator cost (shell + internals, construction and assembling)
2. The heat exchange surface cost (tube bundles)

As a thumb rule, these items can be split in 60 ÷ 70 % for the evaporator and 40 ÷ 30 % for the heat exchange surface, depending on the unit performance ratio and on the type of materials used for both of them.

Now, while the evaporator cost is increasing more or less proportionally to the number of recovery stages due to the weight increase, the heat exchange surface cost is asymptotically decreasing with the number of recovery stages, since the more the stages, the less the surface required for a given distillate production and performance ratio. The combination of these two effects leads to an overall cost curve whose minimum represents the optimal number of recovery stages.
A rather consolidated basic assumption states that the best value for recovery stages number is:

\[ N_{opt} = 2\eta + 1 \]

being \( \eta \) the requested MSF unit performance ratio. In Fig. 4 this rule is shown for an hypothetical plant having a performance ratio of 8.5 kg/2326kJ.

Figure 4: The optimum number of recovery stages

The minimum of the total cost curve (solid black line) depends on the shape of the two relevant curves (dashed black lines) representing the evaporator cost and the heat exchange surface cost. Of course the values constituting these two curves are subject to change as a function of the actual costs of materials and manufacturing, and what was valid ten years ago may be not valid today or in the future. However, the present situation of the unitary costs, and the trends forecast for the short-medium term future, make it possible to draw a second set of curves relevant to the adoption of low thickness titanium tubes and duplex stainless steel (dashed and solid red lines). As it can be seen from the diagram, the results are different both in absolute and relative terms, and with the new materials the above mentioned basic rule seems to shift towards:

\[ N_{opt} = 2\eta - 1 \]

(rather then \( 2\eta + 1 \)) recovery stages. Reducing the number of recovery stages has a side effect which in some cases can constitute a limit to the design: in fact, the increase in the required heat exchange surface must be achieved with a higher number of smaller tubes, but tubes diameter cannot drop below a certain limit to avoid clogging problems, while tubes number cannot increase too much due to vapor side pressure losses. Generally speaking, the use of tube diameters lower than \( \frac{3}{4}'' \) is not advisable for both the above mentioned aspects.

Anyway, apart from any detailed observation, everything is affected by the past, present and future values of the unitary cost of materials and manufacturing. To explain how, more details about the evaluation of the single cost terms and a case study comparison are reported in the following paragraphs.
3.2 The Single Cost Terms

As already anticipated, let’s see how it’s possible to approximately evaluate the two main cost terms:

3.2.1 The Evaporator Cost – In the evaporator cost three sub-items must be taken into account:
✓ the material cost
✓ the construction cost
✓ the assembling cost

As a first approximation, the sum of these costs can be assumed proportional to the evaporator weight, and estimated in a range of 6.5 ÷ 8.0 US$/kg.

On the other hand, the evaporator weight is more or less linear with the unit production, as shown in Fig. 5. The values reported in the above diagram are however valid only for a certain number of stages and in tube velocity. Proper corrections must be applied for different stages number and/or velocities.

3.2.2 The Heat Exchange Surface Cost – In the heat exchange surface cost two sub-items must be taken into account:
✓ the material cost
✓ the construction cost

The material cost estimation is rather easy for many heat exchange materials, based on their composition and on the unitary costs of the raw materials taken from actual market information (see table below).

<table>
<thead>
<tr>
<th>Heat exchange materials composition</th>
<th>Al</th>
<th>Cu</th>
<th>Ni</th>
<th>Zn</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>CuNi 70/30</td>
<td>0%</td>
<td>70%</td>
<td>30%</td>
<td>0%</td>
<td>0%</td>
</tr>
<tr>
<td>CuNi 90/10</td>
<td>0%</td>
<td>90%</td>
<td>10%</td>
<td>0%</td>
<td>0%</td>
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<tr>
<td>AlBr</td>
<td>2%</td>
<td>77%</td>
<td>0%</td>
<td>21%</td>
<td>0%</td>
</tr>
<tr>
<td>Titanium</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>0%</td>
<td>100%</td>
</tr>
</tbody>
</table>

LONDON METAL EXCHANGE

<table>
<thead>
<tr>
<th>Raw Material</th>
<th>Al</th>
<th>Cu</th>
<th>Ni</th>
<th>Zn</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td>US$/kg</td>
<td>1.375</td>
<td>1.595</td>
<td>7.09</td>
<td>0.79</td>
<td>(25,00)</td>
</tr>
</tbody>
</table>

Table 1
The construction cost estimation is more complicated, depending not only on the kind of material, but also on tubes geometric characteristics (length, diameter, thickness). The heat exchange surface necessary for a given production and performance ratio is not fixed, but changes with the number of stages (see the decreasing dashed lines in Fig. 4 above): the higher the number of stages, the lower the necessary overall heat exchange surface.

It is then clear the reason why the total cost curves in Fig. 4 above show a minimum representing the best design solution: increasing or decreasing the stages number brings a benefit on the heat exchange surface cost but worsen the situation for the evaporator cost, and vice versa. But the main issue aimed to cost reduction is where the minimum is located, and this strongly depends on the materials choice according to the market trends, as shown in the following.

IV. A CASE STUDY COMPARISON

4.1 Data summary

In the following, results are reported from a theoretical comparison between a reference plant having 10 MIGD units and 8.5 kg/2326kJ P.R., when designed according to the common practice and materials or with the adoption of low thickness titanium tubes and duplex stainless steel. Data are referred to a single MSF unit, i.e. the total capacity of the desalination plant is given by the unit capacity times the number of units.

<table>
<thead>
<tr>
<th></th>
<th>CONVENTIONAL UNITS</th>
<th>NEW DESIGN</th>
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</thead>
<tbody>
<tr>
<td>Distillate production MIGD</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Performance ratio kg/2326kJ</td>
<td>8.5</td>
<td>8.5</td>
</tr>
<tr>
<td>Operating conditions tbt / swt</td>
<td>105 / 30</td>
<td>105 / 30</td>
</tr>
<tr>
<td>Evaporator material - C.S. cladded</td>
<td>Duplex stainless steel</td>
<td></td>
</tr>
<tr>
<td>Evaporator thickness mm</td>
<td>10 + 3 (roof &amp; bottom)</td>
<td>10 (roof &amp; bottom)</td>
</tr>
<tr>
<td></td>
<td>16 + 3 (side walls)</td>
<td>16 (side walls)</td>
</tr>
<tr>
<td>Evaporator weight (w/o bundles) tons</td>
<td>1,553</td>
<td>1,342</td>
</tr>
<tr>
<td>Evaporator nr. of stages</td>
<td>-</td>
<td>18</td>
</tr>
<tr>
<td>Evaporator length m</td>
<td>78.7</td>
<td>67.0</td>
</tr>
<tr>
<td>Demisters area m²</td>
<td>550</td>
<td>550</td>
</tr>
<tr>
<td>Tubes material - CuNi + AlBr</td>
<td>Titanium</td>
<td></td>
</tr>
<tr>
<td>Tubes ext. diameter mm</td>
<td>32</td>
<td>20</td>
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<tr>
<td>Tubes thickness mm</td>
<td>1.0</td>
<td>0.35</td>
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<tr>
<td>Heat exchange surface m²</td>
<td>122,150</td>
<td>119,750</td>
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<tr>
<td>In tube velocity m/s</td>
<td>2.1</td>
<td>2.9</td>
</tr>
<tr>
<td>Cost of evaporator US$</td>
<td>9,780,000</td>
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<td>Additional costs (pumps) US$</td>
<td>440,000</td>
<td>860,000</td>
</tr>
<tr>
<td>Total cost US$</td>
<td>15,600,000</td>
<td>14,500,000</td>
</tr>
<tr>
<td>Specific cost US$/IGD</td>
<td>1.56</td>
<td>1.45</td>
</tr>
</tbody>
</table>

Table 2
4.2 What’s New?

Now, some important remarks from the data reported in the table:

- The two compared units give the same distillate output with the same heat consumption in identical operating conditions.
- The new design leads to a lighter and shorter unit, however with the same total demisters area.
- The number of stages corresponding to the minimum cost is not the same for the two solutions.
- The velocity inside the tubes is much higher for the new design, increasing as a consequence the heat transfer coefficient but also the necessary pumps head and power consumption.
- Some cost terms are higher in the solution where other cost terms are lower, but the overall cost is lower with the new design.

V. CONCLUSIONS

The reduction of cost for the water produced by desalination processes must be the main target of any research in this field. Many economical models are available to evaluate the water cost, but basically we can state it’s determined by two factors: the capital cost and the operational cost.

While the operational cost is influenced by the amount of energy and consumables necessary to produce the water, plus the maintenance cost, the capital cost depends on the installation cost and lifetime of the plant. Since the evaporator units constitute one of the major cost items for a desalination plant, their reduction in terms of dimension and weight coupled with an increase in their lifetime is a key factor to water cost reduction.

As shown in this paper, both these two goals can be aimed at by re-thinking the design rules of MSF units with the adoption of new materials such as duplex stainless steel and low thickness titanium tubes. Nevertheless, the new design is attractive but not without difficulties still to be overcome, and this should represent an interesting challenge for some of the future researches in the desalination field.

References

1 - C. Sommariva, R. Venkatesh
   MSF Desalination – A review of its development
   Watermark, 18, Dec. 2002

2 - R. Borsani, M. Fazio, M. Accinelli
   Uso del titanio per tubi scambiatore in impianti di dissalazione acqua mare
A NEW DESIGN APPROACH TO REDUCE WATER COST IN MSF EVAPORATORS

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(Fisia Italimpianti)

Presenter: E. Ghiazza
The Water Cost

Water cost can be reduced by:

• New materials
• New technologies
• New design
What’s new

Materials:
- Titanium
- Duplex SS

Technologies:
- Low thickness
Titanium: a low thermal conductivity material?

![Graph showing thermal resistance vs thickness for various materials including CuNi 70/30, CuNi 90/10, and AlBr.](image-url)
The Velocity Issue

Increasing velocity →

- Higher H.E.C.
- Lower bundle cross section
- Lower scaling

but also

higher corrosion rate
A good point for Titanium

Source: HTFS DESIGN REPORT DR56 (1983) "Corrosion in Heat Exchange Equipment"

- Titanium: NO CORROSION
- CuNi 70/30: <25 µm/year, 4.0 m/s
- CuNi 90/10: <25 µm/year, 2.5 m/s
- Aluminium Brass: <50 µm/year, 2.1 m/s
- Stainless Steel 316: <25 µm/year, 1.8 m/s
- Stainless Steel 304: <25 µm/year, 1.8 m/s
Improving MSF efficiency

![Graph showing the relationship between velocity and H.E.C. for AlBr and CuNi tubes.](image-url)
Titanium Drawbacks 1

- Increasing velocity
- Higher pressure drop
  - Pumps power need increasing
  - Limitation by piping thickness
Titanium Drawbacks 2

Materials coupling

Titanium + CuNi

Cathodic protection

Titanium low thickness tubes

Vibration

More support plates
Why Duplex SS?

Evaporator shell & internals in Duplex SS:

- **Structure**: Whole material thickness
- **Joints**: No removal / restoration
- **Welding**: Less equipment / capabilities
Duplex SS Drawbacks

- Slightly higher shrinkening / deformation during welding
- A thickness increase would affect the whole material
How much is the cost of an MSF unit?

- Shell & internals
- Construction
- Assembling
- Recovery tube bundles
- Reject tube bundles
- Brine heater tube bundles

EVAPORATOR COST

HEAT EXCHANGE SURFACE COST
What’s affecting the cost of an MSF unit?

- **Evaporator weight / cost** increases with the number of recovery stages
- **H.e.surface weight / cost** decreases with the number of recovery stages
How much is the weight / cost of the evaporator?

- Shell & internals
- Construction
- Assembling

6.5 ÷ 8 US$/kg
How much is the weight / cost of the h.e.s.?

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- **Tubes Material**
  - From composition and unitary costs
- **Tubes Construction**
  - Varying with length, diameter and thickness
How to minimize the cost of an MSF unit?

\[ N_{\text{opt}} \]

(the optimum number of recovery stages)

- In the past:
  \[ N_{\text{opt}} = 2\eta + 1 \]

- In the future:
  \[ N_{\text{opt}} = 2\eta - 1 \]
An example with $\eta = 8.5 \text{ kg/2326kJ}$
# A Case Study Comparison: the technical point of view

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<td>14,500,000</td>
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<td>Specific cost</td>
<td>US$/IGD</td>
<td>1.56</td>
</tr>
<tr>
<td></td>
<td></td>
<td>1.45</td>
</tr>
</tbody>
</table>
Changing from CONVENTIONAL to NEW design:

- Evaporator weight \(-15\%\)
- Evaporator length \(-15\%\)
- Heat exch. surface \(-2\%\)
Economical highlights

Changing from CONVENTIONAL to NEW design:

• Evaporator cost → - 15%
• H. E. Surface cost → - 3.5%
• Total cost → - 7%
A real improvement

The MSF unit cost can be reduced keeping:

• Same distillate output
• Same heat consumption
• Same operating conditions
• Same demisters area
Conclusions

The use of low thickness Titanium tubes and of Duplex SS for MSF units can definitely reduce the cost of water by lowering the capital cost without affecting the operational cost.

Better materials will also improve the reliability, availability and lifetime of desalination plants.

To reach these goals we have to change some of the design rules adopted since many years.

MSF design can be optimized both from the technical and economical point of view.